MODERN WORLD SERIES

Frontiers of Knowledge

PROF. C. F. POWELL

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D. E. BROADBENT

RICHARD L. GREGORY

PROF. G. M. WYBURN

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CONTRIBUTORS

PROF. C. F. POWELL, F.R.S.
Melville Wills Professor of Physics in Bristol University.

V. A. HUGHES
Assistant Professor of Physics, Department of Physics, Queen's University, Kingston, Ontario, Canada.

PROF. S. K. RUNCORN
Professor of Physics and Director of the Department of Physics, King's College, Durham University.

PROF. B. J. MASON
Professor of Cloud Physics, Imperial College, London.

PROF. A. R. UBBELOHDE, F.R.S.
Head of the Department of Chemical Engineering and Chemical Technology and Professor of Thermodynamics, Imperial College, London.

PROF. C. E. H. BAWN, C.B.E., F.R.S.
Grant Brunner Professor of Inorganic and Physical Chemistry, University of Liverpool.

DR. P. D. COOPER
Director of the Medical Research Council Virus Culture Laboratory, Carshalton, Surrey.

PROF. SIR HANS KREBS, F.R.S.
Whitley Professor of Biochemistry, Oxford University, and Director, Medical Research Council Unit for Research in Cell Metabolism.

PROF. G. P. WELLS, F.R.S.
Professor of Zoology, University College, London.

DR. D. M. ROSS
Head of the Department of Zoology, University of Alberta, Canada.

DR. ERIC J. DENTON
Member of the Marine Biological Association, Plymouth.

DR. A. D. BLEST
Member of the Department of Zoology, University College, London.

DR. GREY WALTER
Director of the Physiological Department, Burden Neurological Institute, Bristol.

DR. R. T. WILKINSON
Member of the Medical Research Council Unit for Research in Applied Psychology, Cambridge.

D. E. BROADBENT
Director of the Medical Research Council Unit for Research in Psychology, Cambridge.

RICHARD L. GREGORY
Lecturer in Experimental Psychology, Cambridge University.

PROF. G. M. WYBURN
Member of the Department of Anatomy, Glasgow University.

CONTENTS

The chapters of this book are based on talks first broadcast by the authors in the European Services of the British Broadcasting Corporation.

The Origin of Cosmic Radiation

BY PROFESSOR C. F. POWELL

1. The Nature of the Problem

Coming out of space and incident on the high atmosphere, there is a thin rain of energetic charged particles which we call the primary cosmic radiation. Experiments during the past twenty years have shown that most of these charged particles are atomic nuclei. We call them *stripped nuclei* because they have lost all the electrons which normally accompany them when they are part of ordinary matter. I say a 'thin rain' of these particles because only a few of them fall every second on every square centimetre at the top of the atmosphere.

We shall be particularly interested in the most energetic of these particles, which approach the earth equally from all directions. Most of the particles are, however, of relatively lower energy and as these approach the earth they are deflected by the earth's magnetic field. As a result, the slower particles tend to be confined to the polar regions, and there are relatively few near the equator. This deflection of moving charged particles as they cross magnetic lines of force is of central importance for current speculations about the mechanism of acceleration of the cosmic rays. Since we now know that any magnetic field round the moon is very weak, and since the moon has no atmosphere, it follows that its surface must be bombarded by cosmic rays of all energies coming equally, or nearly equally, from all directions.

During the past thirty years, the interest in cosmic radiation has been centred on two principal aspects. First, cosmic radiation provides us with a source of particles of much greater energy than any we can produce artificially with the great accelerators. It therefore gives us a technical resource of great importance in the study of elementary particles. When an atomic nucleus is struck by another nucleus of great energy, new types of matter, mesons, hyperons and anti-nucleons may be created at the expense of

the kinetic energy of the incoming particle: there is a transformation of energy into matter

During the past twenty years, because of the great energy of the particles of which it is composed, the study of cosmic radiation has served as a 'path-finder' in the physics of elementary particles. We believe that we now know, or clearly anticipate, all the types of elementary particles which can be made with our present technical resources, and many of them were discovered in the cosmic radiation. As the great cyclotrons and synchrotrons came into operation, they provided us with controlled beams of energetic protons of great intensity, so that we could study the properties of the particles in much more detail than if we had had to rely on the cosmic radiation alone. However, all the time, in spite of the technical advances in the accelerators, we were able to find in cosmic radiation particles of much greater energy than any we could produce artificially; and we were thus enabled to study collisions at much greater energies than in work with artificially generated particles.

Let me put this point more concretely: the proton-synchrotron now in operation at Geneva generates beams of protons with energies up to about 28,000 million electron volts. It appears improbable that, at least during the next five years, and without the introduction of radically new methods, we shall construct accelerators giving particles with energies much greater. By contrast, there are present in small numbers, among the energetic particles of the cosmic radiation, some with at least a million times greater energy—with more than 10,000 million million electron volts. So the processes which result from the collision of atomic nuclei at these great energies can obviously only be studied by means of cosmic radiation.

The second important aspect of cosmic radiation is that with which I am particularly concerned here. The existence of the radiation posed a number of problems in the general field of cosmology of great contemporary interest. Where do the particles originate, and by what physical processes are they given their great energy? Do they come from the sun and similar stars? Are they confined to the galactic systems, or do they pervade the

space between them?

The possibility of making a serious approach to these problems owes a great deal to recent advances in our understanding of the evolution of stars, and of the way the heavier elements of the periodic classification of the chemists are built up from the primeval hydrogen of interstellar space at high temperatures in the middle of stars. A second important new source of knowledge closely related to our problems is radio-astronomy, which has given us a new insight into the structure of our own galaxy—our own star city—and the conditions in the diffuse halo of gas with which we now know it to be surrounded.

Before attempting to speculate about the origin of cosmic radiation it was necessary to establish in detail the characteristics of the radiation arriving at the top of the atmosphere. I have spoken of the radiation as being composed of atomic nuclei. But which nuclei? And in what proportions? We speak of this as the problem of the charge-spectrum of the cosmic radiation. And we need to know it in more detail: how many particles there are with different values of the energy. (We speak of this as the energy-spectrum of the radiation.)

We have known since 1948, as a result of experiments by Freier and others with balloons, that in addition to hydrogen nuclei, which are the most numerous and the simplest of the incoming particles in the primary cosmic radiation, there are also present very much heavier elements. Those up to numbers 26 or 28 in the periodic classification of the elements—nickel and iron—have been detected.

A particularly powerful method of studying the detailed features of the cosmic radiation is to use special photographic emulsions. A photographic emulsion consists of myriads of small crystals of silver-halide, mostly silver bromide, embedded in gelatine. When a charged particle passes through such an emulsion, it changes slightly some of the grains of silver-halide which it traverses, and when the emulsion is developed these particular grains are changed into black grains of silver. As a result the paths of any charged particles which have passed through the emulsion are made manifest. After fixation, washing and drying, the resulting

tracks may be examined under the microscope and photographs of them can be taken.

In practice we do not employ a single layer of emulsion like that on an ordinary photographic plate. We use sheets of emulsion which have been poured on to glass and then stripped off it. These sheets, about half a millimetre thick, are cut to size and then several hundreds of them are packed together, rather like a pack of cards, to make, in effect, a large sensitive block. In a typical case, such a block may weigh 100 kilograms—a volume of 25 litres. Some of the most energetic of the cosmic rays, and the secondary particles which are created when they happen to strike nuclei, may pass right through such a block. When a sufficiently large number of the particles have passed through the block, it is taken apart, the individual sheets are stuck on to glass plates for support, and the emulsions are then developed and fixed in a way similar to that employed in ordinary photography.

With a big stack—25 or 50 litres—this work may take a month and we require several tons of hypo for fixing the plates. When processing is finished, the individual plates can be examined under the microscope. We are thus able to study the tracks produced by the particles which passed through it and see what they did in traversing the emulsion block.

In particular we can identify the tracks made by different kinds of nuclei from the primary radiation and find out their relative numbers. The greater the charge on a nucleus, the thicker and more prominent the track which it produces when it passes through the emulsion. We can make precise measurements under the microscope of the thickness of the tracks. In this way we can determine the charge on a particular nucleus, and thus decide which element it is, with an accuracy of one or two units. We thus know that the heaviest nuclei in the primary cosmic radiation have charges about twenty-eight times that of the electron. Our present methods do not permit us to determine the charge of the nucleus and therefore its nature absolutely accurately, but we are generally not far out. With the lighter elements, like lithium, charge 3, beryllium 4 and boron 5, we can now identify the nuclei with considerable confidence.

Our second technical problem is to make experiments at great altitudes, and hitherto this has been done by balloon. The essential reason is that the great blanket of the atmosphere shields us on earth from the primary cosmic radiation. The heavier nuclei especially cannot penetrate more than a small fraction of the atmosphere without colliding with nuclei of the atoms of air. Such collisions commonly lead to the disintegration of the incoming particles. The original stable assembly of neutrons and protons of such a nucleus is then commonly split up into smaller aggregates so that in place of a single original heavy nucleus we find two or three lighter nuclei. Such disintegrations manifestly distort the charge-spectrum of the incoming particles, and to avoid them we must take our photographic plates to such an altitude that the effect of the overlying air is small. In effect this means that we must make our experiments at an altitude above about 30 km.

2. The Composition of Primary Radiation

In the previous chapter I described the technical problems involved in determining the composition of the primary cosmic radiation—the relative numbers of different kinds of nuclei among the fast particles approaching the earth. We saw that the problem was complicated by the earth's atmosphere which interposes a thick screen of matter, a kind of blanket, between us and outer space, so that the primary cosmic rays as they enter the upper air begin to make collisions with the nuclei of the atoms in it.

As a result of such processes, the nature of the radiation begins to change as it passes down through the atmosphere. An original nucleus of iron, for example, may fragment; it may be disintegrated into two or more nuclei; into lighter elements with smaller charges. The heavier nuclei of the primary radiation, being bigger than the lighter ones, are more likely to make collisions. As a result, the charge-spectrum is distorted, the proportion of lighter elements being increased, and of the heavier diminished. Indeed, very few of the heavier elements are able to penetrate into the atmosphere to altitudes below about 25 km. because of such collisions. If we want to know the charge-spectrum, and this is our main problem, as it is before being modified by such effects, it is clearly necessary to carry our detecting apparatus to such an altitude that the effects of the overlying air are, from this point of view, either eliminated or made very small. There are several ways in which this may be done.

Rockets are able to reach altitudes of more than 80 km. where they are virtually outside the atmosphere, but they suffer from the fact that their time of flight is restricted to a few minutes, and this is too short for the accumulation of sufficient data when using the photographic method of detection. The ideal solution would be to carry a large stack of emulsions on a satellite in an equatorial orbit at a height of about 800 km., and keep it there for about forty days. At present we have to be content to make the

experiments with balloons. I shall speak about this in a later talk.

It is now possible to make experiments with large balloons made of polyethylene or terylene which can carry loads of more than a ton to altitudes above 30 km. and to maintain altitude for 24 hours. In this period, the balloon is likely to drift distances of perhaps 2,000 km. in the upper winds.

Studies of the constitution of the primary cosmic radiation made by these methods have established the main features of the charge-spectrum. Briefly, the most numerous of the primary particles are protons—hydrogen nuclei. In addition, for every 100 protons there are about 10 helium nuclei and about one heavier nucleus. Among the 1 per cent of heavier nuclei in which we are particularly interested, carbon, nitrogen and oxygen, Nos. 6, 7 and 8 in the chemists' periodic table, are the most prominent; and there are about a third as many of the lighter elements, lithium, beryllium and boron, Nos. 3, 4 and 5. Nuclei of the elements from 10 to 26 are represented with approximately equal frequency, although there is some indication that the heavier ones, Nos. 20 to 26, are more numerous than Nos. 14 to 20. Any nuclei above Nos. 26 or 28, if they occur at all, are very rare, but, as we shall see, their presence would be very interesting.

The broad features of the constitution of the cosmic radiation as I have just described them are similar to those of the matter of the universe. We know the relative abundances of different atoms in this general matter of the universe. They have been inferred from observations on the spectrum of the light emitted from the stars, from the constitution of the meteorites which hit the earth, and from the chemical constitution of the earth's crust itself. The light from stars tells us the constitution of stellar atmosphere. There also, in the stellar atmospheres, we find a great preponderance of hydrogen and of helium, together with an appreciable proportion of elements up to nickel and iron, but the heavier elements beyond Nos. 26 and 28 are very rare. If this were all the story, we might conclude that the particles of the cosmic rays are emitted from a typical star like our sun, of which there are about 100,000 million in our galaxy; it would then remain only to enquire how the particles gained their great speeds. But the

situation is more complicated than this, for there are two important ways in which the composition of the cosmic radiation differs from that of average galactic matter.

The first important point of difference is that the cosmic radiation shows about ten times as much nickel-iron, relative to hydrogen, as does galactic matter; nickel-iron is over-abundant in cosmic radiation.

Second, whereas in the cosmic rays the light elements, lithium, beryllium and boron, are present in appreciable quantities—about a third of the carbon and nitrogen and oxygen—they are virtually absent in galactic matter. These two features, the prominence of nickel-iron and the presence of light elements like lithium, have been of key importance in recent speculations about the origin of cosmic radiation. These speculations owe a great deal to the rapid development, especially in the past five years, of our understanding of the evolution of the stars.

According to our present views, a star starts its life as a diffuse accumulation of galactic gas and dust. Under the forces of gravitational attraction between its parts, this matter condenses into a gas ball which becomes hot as a result of the release of gravitational potential energy as the whole mass contracts. When the temperature of the central regions reaches about a million degrees centigrade, thermonuclear reactions involving the light elements, heavy hydrogen, lithium, beryllium and boron, can occur. If such elements are present, they are then very rapidly transformed in a variety of well-known nuclear reactions which we can study in the laboratory. It is reactions of this kind, involving these same elements, that are employed in the hydrogen bomb, and which we hope to harness in thermonuclear reactions, to provide our main source of power for the indefinite future, before, so we hope, we have consumed all our uranium and thorium in our nuclear reactors.

It is because of these processes that the light elements, lithium, beryllium and boron, are present at such low concentrations in the galactic matter. If the cosmic-ray particles originate by ejection from stars, how is it that these light elements appear in considerable concentrations among them? We have for a long time

believed that they are not emitted directly from stars, but that they are the fragmentation products of heavier nuclei. We have seen that a heavy nucleus, in passing through the air, may collide with another nucleus, that of one of the atoms of the air, and fragment to give two or three lighter nuclei; these secondary fragments may sometimes be lithium or beryllium or boron. Similar processes may occur in the passage of the cosmic-ray particles from their points of origin, whatever they may be, to the earth, through collisions with the nuclei of the interstellar gas.

We can therefore suggest a plausible mechanism to explain the presence of the light elements even though they do not emerge directly from stellar atmospheres where we believe them to be absent. They may be produced as a secondary product of nuclear collisions of heavier nuclei. An important point we shall have to consider later is how much matter the primary radiation has to traverse to account for the observed intensity of these light elements.

The second suggestive feature of the constitution of the cosmic radiation, to explain which we may again appeal to recent theories of stellar evolution, is the marked abundance of nickel-iron. We have followed the early stages of stellar evolution in which any lithium, beryllium or boron, if it is originally present, is consumed. Further contraction of the star leads to higher temperatures in the central regions, and reactions can then take place in which the hydrogen is built up into helium.

These reactions occur within a central core of the star where the temperatures are about 15 million degrees Centigrade, and they support the evolution of energy in the star during its main radiating life—of the order of 5,000 million years in the case of a star with the mass of our sun; for more massive stars, this period is considerably shorter. When the hydrogen in the core is all consumed by these processes through the building up of helium, further gravitational collapse, and the corresponding increase in temperature, leads to reactions between these manufactured helium nuclei. As a result we get the building-up of much heavier nuclei such as neon of mass 20 (Ne^{20}) and magnesium of mass 24 (Mg^{24}). In a small fraction of massive stars, this stage is followed

by others in which much of the core becomes composed of nickel-iron.

In such stars when matter has been condensed into nickel-iron, it is, from the nuclear point of view, in its state of lowest energy, and any further nuclear changes can occur only if energy is provided by other sources. If the central temperature, now of the order of 1,000 million degrees Centigrade, is further increased by gravitational contraction, the nickel-iron may be dissociated by the electro-magnetic radiation, some of which, at these high temperatures, is in the form of gamma rays. This involves the absorption of energy and the core rapidly collapses. As a result, the surrounding stellar atmosphere, which still contains much hydrogen and helium, now unsupported through the collapse of the core, falls inwards into the region of very high temperatures near the core.

At these temperatures, the reactions involving the transformation of hydrogen into helium, and others involving the release of neutrons, which at lower temperatures proceeded relatively quietly, now take place explosively, in a fraction of a second. A catastrophe occurs and it only takes a few minutes before a super nova appears in the sky. The whole structure of the star is blown to pieces; it flares up in brilliance so that its intrinsic luminosity for the first thirty days following the explosion is equal to about 1,000 million of our suns.

During the past two years the details of these processes have been closely studied. We find we can account for many important features in the constitution of galactic matter, including the observed relative abundances of the isotopes of many of the chemical elements. These successes give us confidence in the correctness of the essential features of our theoretical speculations. For our present purpose, the important point emerges that it suggests a source of cosmic radiation which could inject into the galactic system fast nuclei, much richer in the heavy elements like nickel-iron than is the average star such as our sun.

3. Super Novae as a Source of Cosmic Rays

I have briefly outlined (above) the main features in the life history of those stars which explode and give rise to super novae, and the reasons for believing that they are an important source of cosmic radiation. The principal point was that they allow us to explain at least one very important and revealing feature about cosmic radiation: namely, the presence in it of heavy nuclei, such as nickel and iron, in much greater proportions than in the ordinary matter of the universe. Other important features of super novae which bear on our problem have been revealed by recent astronomical studies.

Three super novae have been reported in historic times; for our present purpose, the most important was that recorded in the Chinese annals for the year A.D. 1054. The Crab Nebula has been identified as the relict of that stellar explosion. This fascinating object is about 3,000 light years away, and its present radius is about five light years. In ordinary light, it looks through the telescope like an amorphous mass; but when photographed in the light of the hydrogen spectrum (the line hydrogen alpha) it has a complicated filamentous structure. The gas is still rapidly expanding at about 100 km. per second—a speed greater than that of the gas at the centre of an atomic bomb.

The spectrum of the light from some of the central regions of the Crab Nebula shows no line-structure like that emitted from excited atoms. It is a continuous spectrum similar to that emitted by the artificially accelerated electrons, a radiation with which we have become familiar in the past decade, and which we call synchrotron radiation.

Light of this kind is emitted by the beams of particles circulating in circular orbits under the action of magnetic fields in the great synchrotrons. Such accelerated electrons emit light with a colour determined by their frequency of rotation, and with a particular polarisation. The light from the central regions of the Crab

Nebula shows such features. This suggests that there is a marked tendency for magnetic fields to be established parallel to the filamentous structures in the expanding gas, and that there are electrons of great energy moving in roughly circular orbits round the lines of magnetic force.

The observed spectrum tells us of the presence of electrons of energy about 200 million electron volts, and it is reasonable to assume that some of much greater energy are also present. The presence of fast nuclei of even greater energy is even more probable, for they can be accelerated in similar processes to those which give rise to the fast electrons, but they lose their energy much less rapidly than do the electrons of the same speed, because they are much less effective in giving off light, in giving off electro-magnetic radiation, as we say. So, we may assume that a super nova is able to generate fast-moving atomic nuclei with kinetic energies (energies due to movement), equal to some of those which we meet in cosmic radiation, and with a 'charge-spectrum' which is richer in heavier elements than the ordinary matter of the universe because there is so much nickel-iron in a super nova.

The details of the processes whereby electrons and atomic nuclei may be accelerated in the relict of a super nova are at present not understood. A super nova is a very complex structure and the condition of matter in it is quite different from that of which we have much detailed experience in practice: several novel physical processes may therefore be playing an important role. It is known, for example, that 'light pulses', as they are called, regions of higher luminosity, appear to travel outwards from the centre of the Crab Nebula with a velocity of about a tenth of that of light.

These 'light pulses' are thought to represent a kind of 'shock wave' in the diffuse, highly ionised matter—shock waves that are initiated by processes taking place in the small dense star left after the super nova explosion. It has been suggested that they could provide a source of energy by means of which the electrons and atomic nuclei could be accelerated. If, for example, there are magnetic fields associated with them, and directed roughly along the lines of outward motion of the moving pulses, circulating

beams of charged particles could be accelerated by the changing magnetic fields passing through their orbits. We have been made familiar with this kind of betatron action, as we call it, because we use it in some machines for accelerating electrons.

This is a highly speculative field, but very significant, for the processes occurring in highly ionised gas form an important new subject, 'plasma physics' we call it, bearing on current methods of producing very high temperatures. We want these high temperatures for making thermonuclear reactions to occur, in controlled conditions, for the production of power. This is an illustration of the way in which speculations in fundamental physics sometimes have a bearing on practical problems to which, at first sight, they appear quite unrelated. Whether they are fruitful in this particular instance, however, remains to be seen.

Two features of the primary cosmic radiation now remain to be accounted for: the isotropic nature of the radiation approaching the solar system, and the presence in it of lithium, beryllium and boron nuclei, the elements which are almost certainly absent from a super nova immediately before it explodes. Why, for example, if indeed super novae are an important source of cosmic rays, do we not find the particles which reach us tending to come from such a relatively near source as the Crab Nebula? For an approach to this problem we can appeal to some of the findings about the structure of the galaxy based on recent studies of radio-astronomy.

Our galaxy is a spiral nebula, which is something like 70,000 light years across. The stars are most dense near the centre of the system, and the spiral arms are really made up of 'stars' contained in a plate-like disk about 3,000 light years thick. Most of all the matter in the galaxy, about 98 per cent of it, is contained in the stars, but about two per cent of it is in the form of interstellar gas and dust, most of which is in the plane of the galaxy in a layer about 1,000 light years thick. This interstellar matter, gas and dust, is very attenuated; it corresponds to an average density of between about one and ten atoms per cubic centimetre.

In addition to these features, studies in radio-astronomy have shown that surrounding the spiral arms of a galaxy there is a halo of gas, getting thinner and thinner as we move out from the

centre of the galaxy. This halo, roughly spherical in form, about the centre of the galaxy, is more than 120,000 light years in diameter, and the density of the matter in most of it is very much lower than in the disk. Some astronomers guess it to have a mean density of only about one atom per thousand cubic centimetres—one atom for every litre.

The gas and dust in the galactic plane, and in the halo, are not uniformly distributed. As in the Crab Nebula, there appear to be clouds and filaments of matter—irregular concentrations of it. And most important, there are irregular magnetic fields associated with these clouds. The average value of the magnetic field in the galactic disk is estimated to be about a millionth part of a gauss; in the halo it is somewhat less.

As a consequence of these magnetic fields, a charged particle, even of great energy, cannot pursue a straight course in interstellar space. It is deflected by the magnetic fields, and the less energetic the particle the greater the deflection it suffers in a given field. As a result of the actions of these irregular magnetic fields, charged particles emitted from a super nova will be subject to random deflections as they move through interstellar space, and their directions of motion will constantly change. Their progress from their source, from the place where they originate, will be similar to that of a gas molecule in the body of a gas—a random walk with sudden erratic changes in directions—and it is this kind of process which leads to diffusion. This view allows us to account for the fact that at any given point of observation, as we have for example on our earth, the particles appear to be arriving equally from all directions out of space.

Now the limited number of super novae observed in our galaxy, and the frequency of their occurrence in neighbouring galaxies, suggest that they occur about once in every 300 years in any given galaxy. It is something like 300 years since the last super nova occurred in our galaxy and it is reasonable to hope that we shall have a new one before very long. It will be an exceedingly interesting object when it occurs.

We believe they occur most frequently near the centre of the galaxy where most of the stars are, where the star population is

highest, although there is not any definite evidence for this view up to the present. If so, however, the cosmic-ray density will be greatest near the centre of the galaxy and as the particles diffuse outwards towards the periphery of the halo the density of the radiation will become progressively less. Eventually some of the particles, especially the faster ones, may diffuse out of the galactic halo and enter the regions of space between the galaxies. We do not know the distribution of the intensity of cosmic radiation within the galaxy, or the total amount of energy which it represents. So we cannot yet be sure whether the frequency of occurrence of super novae, and the total amount of energy which each injects into the galaxy in the form of cosmic rays, is sufficient to account for the observed concentration of cosmic radiation as we know it.

4. How Cosmic Rays Acquire Their Great Strength

I have described (above) how we established the main features of the cosmic radiation arriving at the top of the atmosphere. We found that there appears to be relatively more nickel-iron nuclei in the radiation than in the general matter of the universe, and that this can be accounted for if the radiation is originally injected into the galaxy from super novae. They may also come from other stars such as the so-called magnetic variables. We saw too that we can account for the fact that the radiation appears to reach the solar system equally from all directions. Although it can originate from individual super novae, it does not travel directly to the earth. The particles are deflected in interstellar space under the action of the magnetic fields associated with the wandering masses of diffuse gas—attenuated clouds of gas and dust—and these deflections stir up the particles, as it were, so that their directions of motion become random.

As a result of such processes we do not find a lot of cosmic-ray particles arriving at the earth from the direction of the Crab Nebulae, one of the nearest of the recent super novae, although we believe that it is continuously injecting cosmic rays into space at the present time.

The picture of the stirring-up of the cosmic rays in interstellar space, under the action of the weak but extended magnetic fields which we believe to exist there, also has an important bearing on the problem of the presence of the light elements, lithium, beryllium and boron, in the primary cosmic rays reaching the earth. We have seen that these elements are very rare in the matter of the universe because they are consumed in the thermo-nuclear reactions taking place in the early stages in the life of a star. We have also seen that we can account for their presence in cosmic radiation by assuming that they can be reproduced when heavier nuclei pass through matter. The heavier nuclei, colliding with the nuclei of a gas for example, may fragment and give rise

to lighter nuclei including those of elements such as lithium. This happens when the cosmic rays enter our own atmosphere, and make it necessary, as we saw, to carry our apparatus virtually above the atmosphere. However, the light elements which arrive at the top of the atmosphere certainly have not been formed in the atmosphere. They may, though, be attributed to similar collisions with nuclei, and the problem is: where did these collisions occur?

It is tempting, at first sight, to assume that these nuclear collisions may have taken place whilst the particles were still being accelerated in the relict of the super nova. But this seems unlikely for the following reason.

If we are right in attributing the light elements in the cosmic rays to nuclear collisions made by heavier nuclei, then we can estimate how much matter must have been penetrated in order to account for the observed proportions of lithium, beryllium and boron. Let us, for example, make the extreme assumption that all the cosmic-ray particles begin as nuclei of nickel or iron. Then we find that after they have penetrated through a layer of hydrogen of such a thickness that every square centimetre of the layer weighs 10 grams, then the lithium and beryllium will be produced, through fragmentation, in approximately the proportions observed. It does not matter, from this point of view, how the layer of matter—we have considered hydrogen—is spread out along the path of the moving heavy nuclei. What matters is that if all the matter in a column of area one square centimetre around the path of the particle were pressed together, it would weigh 10 grams.

The above value, 10 grams, was based on the extreme assumption that all the cosmic rays start out as nickel—or iron—nuclei. A more realistic assumption gives a value of only about four or five grams of hydrogen. Now the density of matter in the relict of a super nova is so small that, taking into account its size and the probable time that a nucleus spends in it whilst being accelerated, it seems unlikely that the average particle penetrates nearly as much as five grams per square centimetre of matter before it escapes into space. It seems much more likely therefore that most

of the fragmentation takes place as a result of collisions during the very long time which the particles spend in their random journey, as they wander about—whilst being deflected by the magnetic fields in the tenuous gas clouds in interstellar space.

Although the gas in the interstellar space is so diffuse, if the particles wander in it for a sufficiently long time they can be made to penetrate any desired amount of interstellar hydrogen. And, to be more precise, if we know the density of the interstellar hydrogen, we can estimate the average time taken by a particle to penetrate a layer of total weight five grams per square centimetre, during its journey from its point of origin to the earth.

It is here that we meet a difficulty. There are two ways in which we can hope to find out the value of the density of hydrogen in the galaxy. We are interested in hydrogen nuclei and it does not matter if they are present as ordinary atoms, each with its nucleus and an attendant electron; or as hydrogen ions—that is, bare hydrogen nuclei from which the electron has been separated. We can hope to estimate the density of the bare nuclei by studying the intensity of the radio waves of a particular kind which reach us from the distant parts of the galaxy. And, further, we can find the density of the hydrogen atoms from the radio emission of a quite distinct and different kind which they send out, the famous hydrogen line with a wavelength of 21 cm.

At present these radio methods do not give us sufficiently certain information about the density of hydrogen nuclei throughout the galaxy. However, some of the best authorities guess that the average value in the interstellar space in the plane of the galaxy—in the galactic disk as we call it—is between one and ten atoms per cubic centimetre; whereas, in the galactic halo it is something between one and ten per litre. If these values are approximately correct, and if the cosmic rays spend most of their time wandering in the galactic halo, then their average age—the average time elapsing between their moments of generation whenever in space that may be and the instant they reach the earth—is some thousands of millions of years. On the other hand, if they are confined to the galactic disk their age is some millions of years only. Let me emphasise that at present these estimates are little more than

guesses, and we shall all be most interested in more precise estimates which may follow from improved measurements in radio-astronomy.

The wandering of the particles of the cosmic radiation in interstellar space may also play an important role in their acceleration. About ten years ago the Italian physicist, Fermi, working in America, suggested a mechanism for the acceleration of cosmic rays based on the following idea. He showed that the deflection of the particles by the magnetic fields of wandering gas clouds would, on the average, lead to an acceleration of the particles. The longer the period of wandering, the greater the energy a particle would acquire. It is possible that this mechanism is important in leading to the particles of greatest energy which arrive at the earth.

One of Fermi's difficulties was to find a mechanism whereby the particles could be given sufficient initial energy so that his mechanism would begin to work at all; until the nuclei reach a certain energy they tend to be slowed down, through ionisation, as they move through the diffuse clouds. Now we have a plausible mechanism of injection—from the super novae—and his mechanism may perhaps take over.

From the account I have given, you will see that we have no finally established picture of the origin of the cosmic rays, but we do know a good deal about them, and we can give a plausible account of how they originate and gain their great energies. Let me conclude by saying something about our outstanding problems and how we hope to resolve them.

First, we should like to make a search for the arrival of nuclei heavier than nickel or iron. One way of doing this is by observations with counters carried by satellites. This search will be arduous, for these even heavier nuclei must be very rare if they occur at all. Indeed, it has been reported that, in such an experiment carried out on a satellite by our Russian colleagues, a single pulse due to such a heavier nucleus was detected in the whole course of the experiment.

Second, we should very much like to gain more detailed knowledge of the mass-spectrum of the primary cosmic radiation

by methods similar to those with photographic emulsions which I have already described—similar experiments but of greater precision. For this, a large stack of emulsions carried on a satellite in an equatorial orbit at a height of about 1,000 km. would be of great value. To be useful, however, it would be necessary to return the stack of emulsions to the earth and to recover it without damage, after it had been in orbit for about 20 days. For the moment this is a problem for the future, for although the problem of re-entry through the earth's atmosphere has been solved, the load would be great and space on satellites is very valuable.

The work which I have described in these talks is the result of what, in effect, is an extensive collaboration, which has involved British, Russian, American, Japanese and other scientists. I might mention in particular the names of Ginsberg and Hayakawa and Peters who have contributed very much to recent theories we have been discussing.

Much has been achieved, but much remains to be done. I hope, however, that I have shown you the fascinating way in which studies of cosmic rays have linked up with the problem of the evolution of stars and of the structure of the cosmos. This great development reminds me of a remark made by my old teacher J. J. Thomson, and his son G. P. Thomson, in their book on the electrical conductivity of gases which was written more than thirty years ago. Discussing in that book the early evidence for the view that we are indeed bombarded by a radiation coming from out of the depths of space, they said: 'It would be one of the romances of science if the study of these remote and prosaic leakages of electricity from well-insulated bodies should be the means whereby some of the most fundamental problems of the cosmos came to be investigated.' Surely in view of the present state of our knowledge we may say that they spoke with most remarkable foresight.

How Rough is the Moon?

BY V. A. HUGHES

Near the end of the second world war various scientists in different lands considered the possibility of using radar as a means for probing the solar system. If it were possible to bounce radar signals off the planets and receive them back at the earth then it should be possible to measure the distance of the planets more accurately and also find out more about their surface conditions.

Obviously the first planetary body to be considered was the moon which, though it is 3,476 km. in diameter, is at a distance of about 400,000 km. and so very much farther away than the few hundred kilometres at which aircraft had been detected. This would mean a very large improvement in the performance of the radars.

Now the ease with which we can detect the radar echo depends on the product of transmitted power and pulse length, and since only limited transmitter powers were available it was necessary to use very long pulses. Of course, large aerial systems and sensitive receivers were also required, but in this way radar contact was made with the moon by the United States Signal Corps in 1946, and also independently by Bay in Hungary.

In 1949 a more extended series of measurements was carried out in Australia, and this time the radar pulses were transmitted from the radio station, 'Radio Australia'.

The Australian measurements, which were at a wavelength of 15 metres, showed that the radar echo from the moon was not steady but fluctuated in amplitude with both a short and long period fading. The long period fading was later shown to be due to the effects of the ionosphere, but the short period fluctuations were assumed to be due to the slow rocking of the moon which we call lunar libration. Due to the long pulse length the whole of the moon's disk was covered by each pulse, and the combination of reflections from the whole of the surface could account for the fluctuations.

In a series of experiments carried out at Jodrell Bank, Evans separated the various frequency components. He found that there was a marked absence of the expected higher frequency fluctuations and concluded that most of the radiation was being reflected from the central part of the disk.

Now in 1957 there had been constructed, at the Royal Radar Establishment in Malvern, a radiotelescope with a parabolic aerial 13·7 m. in diameter. Although not large in comparison with some other telescopes, it had a more accurately shaped surface and could be used at the short wavelength of 10 cm. where it produced a much narrower, and hence more intense, beam of radiation than had been obtained at the longer wavelength of 15 metres. Installed in the telescope was a powerful 10 cm. radar with a power of 2 MW but a pulse length of only 5 microseconds. This short pulse length enabled objects to be resolved which were separated in range by less than a kilometre. However, though the beamwidth was narrow, as far as radio beams are concerned, it was still $\frac{1}{2}°$ across and approximately equal to the angular diameter of the moon. The radar echo obtained would hence be that from narrow annular or ring-like regions which move out from the centre of the projected disk, corresponding to the pulse moving across the surface.

When the telescope was directed towards the moon it was indeed found that instead of a band of echoes stretching for a distance of 1,738 km., corresponding to the radius of the moon, the echo consisted of a sharp increase as the pulse reached the front surface, followed by a very rapid decrease in intensity until after a distance of about 50 km. it had fallen to a level which was ten times down on the initial value. The general appearance was of a series of spikes, each equivalent to the length of the transmitted pulse, which fluctuated at the frequencies that would be expected, and a closer examination showed that no one region of the moon appeared to give a consistent echo.

Now let us consider how we might expect the radio waves to be scattered. Initially, because most of the moon is covered by mountains and craters, we might expect to receive a number of individual echoes from most of the surface, but this, as we have

mentioned, would not appear to be borne out by the observations. Let us then consider two extreme cases. First we will assume that the surface may be completely rough, by which we mean that it consists of a large number of small surface features of a size comparable to the wavelength used. In this case we would again expect to receive echoes from the whole of the surface similar to the way that we can see the reflected light from the moon over the whole of its disk, though of course with light the wavelength is over a million times smaller. At the other extreme, if we assume that the surface is completely smooth, then diffraction theory tells us that we would only receive an echo from the very small region of the surface nearest to the earth. It would appear from the observations that the surface must be intermediate between these two extreme cases.

Let us then define the surface statistically and in terms of two parameters: one parameter to describe the deviations from a smooth surface in the vertical direction, in other words the amplitude of the irregularities, and the other the mean interval between the irregularities or the scale. Now a theoretical treatment shows that the angular scattering law, that is the amount of power reflected back to the radar by the surface at different angles of incidence, depends on the amplitude of the irregularities as well as on their scale. The greater the amplitude, or the smaller the scale, the rougher the surface becomes, and the more the reflected power at greater angles from normal incidence. For small amplitudes the angular scattering property depends on the radar wavelength; but if the irregularities are much greater than the wavelength, then the scattering law is not dependent on wavelength but on the ratio of amplitude to scale, in other words to the distribution of slopes on the surface. Hence, it should be possible to determine the type of surface on the moon by measuring accurately the angular scattering law, and comparing the results for different wavelengths.

The scattering law may be determined quite simply, since as the radar pulse travels across the moon the angle of incidence changes from being normal at the point nearest the earth to glancing angle at the limb. By converting the distance from first

contact with the moon to angle of incidence, we obtain the scattering law.

Because the intensity of the echo decreased rapidly to very small values, it was necessary to increase the sensitivity of the radar and a special integration technique was developed, but we were now in a position to compare our results with other results obtained at longer wavelengths but where longer pulse lengths had been used. It was found that the scattering law for the wavelength of 10 cm. was similar to that obtained at the wavelength of 1·5 m. by Trexler in the United States. As we have explained this would be consistent with scattering from a surface on the moon that had vertical irregularities much greater than the wavelength of 1·5 m. We can hence assume a minimum value for the amplitude of about ten times this longer wavelength, in other words about 15 m.

The scattering law would also be consistent with a surface where the majority of the slopes are less than about 8°, and hence the scale or interval between the irregularities is probably at least 100 m. Some more recent measurements in the United States, at a wavelength of 3 cm., suggest that the scattering law is beginning to depart appreciably from that at the longer wavelengths and hence that the surface may also have a granular structure, the dimensions of the granulations being about a centimetre.

To obtain a fuller picture of the surface structure we have, of course, to consider optical observations. The more recent, using telescopes to measure the change in the lengths of shadows cast by the various large-scale features, are limited in resolution to distances greater than about 500 m. due to the effects of the terrestrial atmosphere. They do, however, show slopes with small gradients similar to those derived from the radar observations.

We would say that there must be very little small-scale structure on the surface, apart from small granulations, and the interesting conclusion arises that not only must most of the surface of the moon be comparatively flat consisting of an undulating surface with the majority of slopes less than about 8°, but these gradual slopes probably extend for distances of the order of kilometres. Not only would the moon appear to be a dead planet, with no

atmosphere, but it would also appear to have an extremely flat and uninteresting topography. We know that there are craters present and mountain ranges that reach to heights of many kilometres, but unlike the earth which has been subjected to storms and torrents which weather the peaks of mountains and to the succession of ice ages where glaciers scour out the valleys, the lunar mountains and craters must have very gradual slopes; they must be far less impressive than the mountains we see on earth.

We have seen how it is possible to determine certain properties of the lunar surface by using radar waves sent out from the earth, and how these measurements can compliment observations using optical waves. We cannot, of course, see the other side of the moon and this must be left to rocket investigations of the kind first carried out in 1960 by the Russian Lunik. However, we have also a means of determining some of the surface properties and rates of rotation of planets and especially those that are covered by optically obscuring atmospheres, such as Venus. This, together with the more accurate measurement of planetary distances which also has been accomplished using radar, can assist the celestial navigation and the successful landing of space rockets.

To obtain radar echoes from Venus, our nearest planet, requires an improvement of 10 million times over a moon radar, but this has been done in both Britain and the United States. With further improvements in sensitivity, higher transmitter powers and larger aerials, it should be possible inside the next ten years to obtain radar contact with most of the planets and minor planets. The time of flight of the radar pulses will not be about three seconds as for the moon, but five hours or more in the case of the outer planets.

Radar contacts with the sun are also an indication of how we can make use of radar to investigate parts of space which are inaccessible to space rockets.

Radar has gone a long way from the detection of aircraft in the early days of the second world war, but it has still further contributions to make to the fascinating subject of space research.

Why the Continents Move

BY PROFESSOR S. KEITH RUNCORN

If you have ever examined a globe carefully you must have been struck by the similarity in shape of the Atlantic coasts of South America and Africa: they seem to fit together. Fifty years ago a German meteorologist, Alfred Wegener, made this simple fact the basis of a theory of how the surface of the earth has evolved—the theory of continental drift. He supposed that in earlier geological times the continents of the southern hemisphere and India were joined into one great continent, Gondwanaland. It broke up and dispersed only in the comparatively recent history of the earth, 100 or 200 million years ago. In the same way, Wegener supposed that Europe and North America had also been a single continent.

Of course Wegener had many other reasons for postulating this remarkable theory of continental drift.

In the early nineteenth century the newly developing science of geology had had a great triumph. Geologists had demonstrated that North Europe and North America had been covered quite recently by advancing and retreating ice sheets. We now know that these Ice Ages started about one million years ago. Geologists quickly became highly skilled in recognising (in rocks) the signs of the action of ancient glaciers. So you can imagine the astonishment caused when British geologists who had gone out to survey abroad announced that they had discovered such tell-tale signs of glacial action close to the present equator in India, Australia, Africa and South America. These finds were all made in much older rocks—similar in age to our coal measures—rocks of what geologists call the Permo-Carboniferous period.

These results posed a problem. The ice traces in the Permo-Carboniferous rocks were spread over wide areas of four continents. How had they got there? It was natural for the more speculative minds to try to find an explanation. One might, of course,

suppose that the whole of the earth at this time was cold, perhaps due to a fluctuation in the amount of sun's radiation reaching the earth. But there is evidence that the northern hemisphere had simultaneously enjoyed a warm climate. And so a bolder hypothesis was considered: that the pole around which the earth rotates had changed in such a way that these glaciated continents were once in high latitude. This was the theory of polar wandering.

This theory, however, was not adequate, for if you experiment with a globe you will see that there is no position of the pole which will bring all the four continents into high latitude at the same time. And so Wegener took the further bold step of supposing that these continents were at one time very much closer together.

Not only do the outlines of South America and Africa fit, but the geological deposits seem similar, as if they were laid down together. Wegener also noticed that the fossils in the Permo-Carboniferous rocks of the four continents were very much alike, and he suggested that the original organisms might have lived in the same environment.

And so the theory of continental drift was born: its importance and originality led to considerable controversy in the 1920s. But the geological evidence was not decisive, and by the second world war most geologists had decided against the theory.

At the same time, a powerful new science was developing—geophysics—the use of the methods of theoretical and experimental physics in understanding the earth. Now, whereas the geologists could only make qualitative statements, the geophysicist made quantitative ones. The geologist said that the Permo-Carboniferous glaciation was very old; the geophysicist said it was 250 million years old. The geologist might wonder if continents could really drift apart. The geophysicist thought that he knew enough about the properties of the earth to say whether this was possible. In the 1930s, geophysicists considered the idea of continental drift and rejected it.

Their reason was an interesting one. Geophysics was then developing by the study of earthquake records, particularly by timing the travel of the various kinds of waves through the earth. From this, the elasticity of the earth at all depths has been

calculated, and it has been found to consist of a liquid core, probably of molten iron, and a little over half the earth's radius. The core is enveloped by a mantle of heavy rock, on which the lighter rocks of the continents float. The mantle, unlike the core, was found to be solid; it could transmit shear waves—waves of torsion. Besides, the earth wobbles a bit on its axis, like a top, and it could not do this unless the equatorial bulge is very rigid.

So earth scientists dismissed the possibility of continental drift—the mantle was solid—it just could not happen. Just as they were banishing the idea, however, research was beginning into an entirely different branch of geophysics—research which was to bring the theory back into favour, the branch of paleomagnetism.

The earth's magnetic field has been a favourite study in this country ever since 1600, when William Gilbert, physician to Queen Elizabeth I, wrote his famous treatise *De Magnete*. Gilbert showed by a simple experiment that the compass needle points north because the earth is a great magnet. Measurements made over the world since then have given us a good idea of the behaviour of the field. Though its direction is approximately north, it is not exactly so and, for example, in London today it points 11° west of north. What is more, the field is continually changing: in London it was twenty-four degrees west in 1800; it was pointing due north in 1650; and east of north before then. This so-called secular change is complex and rapid—as geological times go—and we now know, through the work of Sir Edward Bullard and others, that it is due to turbulence in the fluid iron core. But the earth's age is over 4,000 million years, so our observation of the field only extends over the last one ten-millionth of its lifetime. What happened to it in the past? Fortunately, a record of this has been preserved for us.

Most rocks contain a small percentage of iron in the form of oxides which are not as magnetic as iron, but they can retain any magnetism they pick up. Now, it so happens that many rocks, especially lavas and red sandstones, become magnetised when they are formed, and their magnetism, of course, is in the direction of the earth's magnetic field at that time. Lavas which have

erupted in recent years are seen to magnetise as they cool. Consequently, if you select rocks of various ages, and take samples from them, carefully noting their orientation, you can measure their very weak magnetism, and so investigate the earth's magnetic field in the remote geological past.

The first rocks to be investigated in this way were lavas of the last few tens of millions of years, those in Iceland, in the states of Washington and Oregon, in Victoria, Australia, and in the Antarctic. All (on the average) had magnetisations pointing exactly due north. This confirms the theory that the secular change averages itself out over long periods. The mean magnetic and geographic poles coincide. But if we go further back into geological history, the mean magnetisation of the rocks departs from the present north.

This new subject of paleomagnetism enables us to track the movement of the magnetic poles relative to the continents. It is now established that the North Pole has moved at a rate of about a third of a degree per million years round what is now the north Pacific basin—600 million years ago it was near Hawaii.

You will see the connection between continental drift and paleomagnetism. Magnetism gives a fix on the position of the North Pole relative to the continents, and the ancient magnetic results show that this has changed. What is more, if we consider rocks more than about 100 million years old, we find that the track of the Pole based on American rocks is some 30° west of the track based on British rocks. The only way to close up these curves is to suppose that the Atlantic, about 150 million years ago, was about half its present width. In a similar way, Irving has shown that Australia was at the South Pole in Permo-Carboniferous times—and this fits in well with the evidence from glaciation that I mentioned earlier.

And so the geophysicist has, through paleomagnetism, restored the theory of continental drift to a key place in our thinking about the earth's evolution. But what about the geophysicists' proof of its impossibility? This was founded on an old-fashioned view of what a solid is. There are solids like pitch which will flow if they are left long enough, and the earth's mantle has this property. In

fact, evidence for this has really been available for a long time. For a century it has been known that the light rocks of the continents, the granites of which the continents are mostly made, are floating in the basic heavier rocks of the mantle, just like ships in water. When a ship is unloaded it rises and the continents do the same. Ten thousand years ago, Scandinavia and Finland were relieved of a thick covering of ice, and they have been rising slowly ever since.

But what makes the continents drift sideways? When a pot of porridge is being heated, the fluid at the bottom becomes less dense and rises: it is replaced by the colder fluid from the top: so with luck the porridge does not burn. This is a familiar process in physics called convection, and something like it is evidently happening in the earth. Heat, probably the result of radioactivity, is escaping from the earth, and it is causing great convection currents in the mantle. Only two or three years ago there was assumed to be no evidence for any such currents, but recently oceanographers have come to the conclusion that a great upswelling current lies below the mid-Atlantic ridge. It divides, part moving to the west, and part to the east, and it is gradually pulling the Atlantic floor apart.

The result is a deep central valley in the mid-Atlantic ridge, below which basalt is solidifying. This in turn creates a magnetic disturbance, which can be detected from the air. These currents are falling under the continents, and this is in fact why the continents are where they are now. But why were they in different positions 100 or 200 million years ago?

I referred earlier to the earth's iron core: its radius is now just over half the earth's radius. It cannot always have been this size. Professors Hoyle and Urey have given cogent reasons for believing that the earth did not cool from a sphere of gas, but gradually accumulated from iron and silicate bodies, rather like the iron and stone meteorites which still fall to the earth from time to time.

Such an accretion theory has one serious difficulty—it does not suggest how the iron gradually collected in the centre. But the convection currents help here, as they will tend to leave their

heavier constituents near the centre. At all events, the iron core will grow slowly. When the core was small, the convection currents would rise at one pole and sweep towards the other. This would drag the continents together—away from the point under which the current was rising. This is probably why there are today no continents in the Pacific hemisphere. But long before the earliest date which geologists can study—about 600 million years ago—the core would have grown too large for this simple convection pattern, and a more complicated system of currents would take its place.

One thousand million years ago, on this theory, another stage of increasingly complicated convection was reached, and again about 200 million years ago. It was probably this last transition in the convection pattern in the earth's mantle which dispersed the continents to their present position. Whether or not this convection theory is correct I believe that the study of continental drift will continue to be the main spur to research into the evolution of our planet.

The Generation of Electricity in Thunderstorms and the Origin of Lightning

BY PROFESSOR B. J. MASON

It was in 1752 that Benjamin Franklin and the French physicist d'Alibard first showed that electricity was present in thunder-clouds, and ever since the origin of this electricity and of the lightning flash has remained conspicuous on the list of unsolved scientific problems.

In principle, the thunderstorm may be regarded as an electrical generator which produces electric charges, both positive and negative, and separates these so that the positive charge appears in the upper regions of the cloud and the negative charge lower down. As separation of the positive and negative charges proceeds, the voltage difference between the two oppositely charged regions, or between one of them and the earth, grows until it reaches 100 million or even 1,000 million volts when the insulation of the air breaks down and a lightning flash occurs. At least part of the separated charge disappears during the passage of the lightning discharge. The charge then builds up again and the same sequence of events is repeated.

In principle, then, the operation of this 'natural dynamo' is simple, but the detailed mechanisms of charge generation, separation, and dissipation are very complex. There is certainly no shortage of theories, but none has withstood the test of time and the accumulation of more detailed information on the structure and behaviour of thunderstorms. A satisfactory theory must explain how electric charge is generated and separated at a sufficient rate to account for its dissipation by lightning. It must also account for the observed distribution of positive and negative charges inside the thundercloud and the observed changes in electric field produced by lightning flashes.

The distribution of electric charge inside a thunderstorm was first deduced about 1920 by C. T. R. Wilson who studied how the electric field produced at the ground by lightning flashes varied with the distance from the storm. He concluded that there was an upper positively charged region and a negatively charged region lower down in the cloud. This general picture has since been confirmed by many scientists in different parts of the world. In particular, I would mention Sir George Simpson, who sent up balloons fitted with an instrument to measure how the direction and strength of the electric fields inside thunderclouds varied with height. Simpson found that the upper positive charge was usually associated with temperatures below -20° C. and the lower negative charge with temperatures just below 0° C. In other words, separation of the charges took place in regions of the cloud where the temperatures were below freezing. This fact will be important when we come to discuss the origin of the charge.

A lightning flash may either travel from the cloud to the ground, or may occur entirely inside the cloud. Because of the very great speed with which lightning travels, the structure of a flash can be studied only with the help of a very fast camera. Photographs taken with such a camera show that a lightning flash may consist of a number of successive strokes which follow one another along the same track at intervals of a few hundredths of a second. The average number of separate strokes is three, but I believe that as many as fifty have been recorded.

A lightning discharge reaching the ground is started by a streamer which travels from the bottom of the cloud in a series of steps. Each step can be seen on the photograph by a sudden increase in the brightness. This stepped-leader stroke, as it is called, approaches the ground at about 100 km. per second, often along a zig-zag path with downward-pointing branches—hence the term forked lightning. When this leader stroke reaches the ground, the main or return stroke travels up the path established by the leader. This return stroke is much brighter than the leader and travels at about 30,000 km. per second—one-tenth the speed of light. It is this stroke which causes all the damage for it may carry a current of 10,000, or even 100,000 amperes. So,

during this very short period, the thunderstorm dynamo has a power output of about ten million megawatts. After a pause of a few hundredths of a second, there may be a second leader and return stroke, and the whole process may be repeated a number of times.

The structure of a flash occurring entirely inside the cloud is usually obscured by the cloud itself so that we see only a general diffuse light. This we call sheet lightning. The air in the narrow lightning channel which, incidentally, is only about 20 cm. wide, is heated within a few ten-millionths of a second to a temperature of about 15,000° C., that is, two and a half times hotter than the sun. The air in the channel expands explosively to create intense sound waves which we hear as thunder.

Violent electrical activity in a thunderstorm is usually accompanied by heavy precipitation in the form of hail or rain and most of the theories of charge production assume that the precipitation plays an important part. And, since the main charge centres appear at levels in the cloud where the temperature is below 0° C., it is natural to associate charge production with the growth of ice particles. Indeed there is increasing evidence that lightning and strong electric fields in clouds coincide with the appearance of particles of soft hail.

The manner in which the electric field recovers after the passage of the first lightning flash indicates that about 1,000 coulombs of electricity have already been generated and are undergoing separation at this time. Incidentally, a coulomb of electricity is the quantity which passes when one ampere flows for one second. Presumably this charge is generated within the ten- to twenty-minute interval which elapses between the formation of rain and hail within the cloud as seen on a radar screen and the appearance of the first lightning flash. Radar also gives us information on the size of the storm; a modest thunderstorm may have a volume of about 100 cubic kilometres. This all implies, in round figures, an average charging rate of about one coulomb per cubic kilometre per minute.

The various charging mechanisms which have been suggested in the past appear incapable of producing charges at anything like

this rate and, moreover, are just not in accord with our modern knowledge of the structure and behaviour of thunderstorms.

In searching for a new mechanism, I was particularly impressed by the following clues:

First, the main charging mechanism is probably associated with precipitation—most likely soft hail formed by the impaction and freezing of cloud droplets in the supercooled state. As I have already indicated there is increasing evidence that the appearance of soft hail in a cloud is accompanied by strong electric fields and lightning.

Second, laboratory experiments performed by W. Findeison in Germany during the last war and repeated by others since have shown that, when supercooled water droplets are sprayed on to a cold surface to produce a layer of rime ice, the rime acquires a charge and the air acquires a charge of opposite sign.

And thirdly, in some recent experiments Dr. Maybank and I have found that the freezing of small water droplets is often accompanied by the ejection of small splinters of ice carrying a positive charge, leaving a negative charge on the remainder of the frozen droplet. This suggests that the formation of pellets of soft hail in a cloud by the impaction and freezing of supercooled drops will lead to the formation of negatively charged hailstones which will fall to the bottom of the cloud, while the small positively charged ice splinters will be carried by the strong air currents towards the top of the cloud. You see, such a mechanism would give the cloud its observed distribution of charge—positive above, negative below.

In the last two years, Dr. Latham and I have measured, in the laboratory, the rate at which artificial hailstones become charged by the impaction and freezing of supercooled water droplets. The experiments were conducted in a cold laboratory at temperatures down to about -20° C. The simulated hailstone, a small sphere of ice, was held stationary in a wind tunnel as supercooled droplets of from 1/50th to 1/10th of a millimetre in diameter were blown past it at speeds varying from 1 to 30 metres per second.

As we expected, the freezing of the droplets on the hailstone caused it to become negatively charged, a compensating positive

charge being carried away in the airstream by small ice splinters. We measured how the quantity of charge and the number of ice splinters produced varied with the size and impact velocity of the droplets and with the temperature of the hailstone surface. With these data we were in a position to calculate the probable rates of charge generation which might be associated with the formation of soft hail in a typical thundercloud.

From aircraft measurements we have a fair idea of the number of hail pellets and supercooled cloud droplets to be found in a given volume of the cloud. We can therefore calculate the rate at which the more rapidly falling hailstones will collide with supercooled droplets and, using our laboratory results for the charge produced by each such collision, we can compute the rate at which the hailstones will acquire negative charge. Finally, we can calculate the rate at which the charge, and the electric field produced by separation of the positive and negative charges, build up. It turns out that this mechanism can readily generate electricity at the required rate of one coulomb per cubic kilometre per minute. Accordingly, we believe this to be the principal mechanism of thunderstorm electrification.

But there is a very important question which I have not yet answered. Why should the ice splinters ejected from a freezing droplet be positively charged and the remainder of the droplet negative? Why not the other way round? How is this separation of positive and negative charges achieved during the freezing process? We have discovered that it results from the fact that the freezing droplet is not at a uniform temperature. If we imagine a piece of ice with its ends at different temperatures, more of the ice molecules will dissociate at the warmer end and so this will possess initially a higher concentration of both positive hydrogen ions (protons) and negative hydroxyl ions than the colder end. Ions of both types will therefore tend to diffuse from the warm to the cold end but, because the positive ions travel about ten times faster than the negative ions, these move ahead, and cause an excess of positive charge to accumulate in the colder part of the ice; there will be corresponding negative charge in the warmer end. In other words, a potential difference or a voltage will be

created across the piece of ice and, in fact, we have been able to measure this.

Now let us return to our freezing drop. During the early stages of freezing a shell of ice is formed on the outside of the drop, the interior of which remains liquid. The temperature of the inside of the shell is therefore 0° C., but its outside is colder. Under these conditions, the more rapid migration of positive ions will produce an excess of positive charge in the outer layers of the ice shell. When the droplet bursts by expansion of the freezing centre, splinters are ejected from the outer layers and carry away some positive charge and so leave the remainder of the drop negative. This is just what we observe.

What we are really saying is that the large-scale generation of electricity in a thunderstorm fundamentally depends upon the rapid migration of positive ions in ice under small differences of temperature. This is a nice link between atomic physics and physics on the grand scale of the thunderstorm.

Why Solids Melt

BY PROFESSOR A. R. UBBELOHDE

Primitive man knew about ice melting in warm weather. Cooks have known about the melting and solidification of fats, and metal-smiths about the melting of bronze for thousands of years. In spite of this long experience, understanding of why solids melt has been reached only quite recently.

Some of the more general facts about melting were established quite early in the history of science. It was found that at a given pressure there is only one melting temperature at which specific solid and liquid states of the same pure substance can exist in contact, without either growing at the expense of the other. On passing from solid to melt there is an abrupt absorption of energy in the form of heat; this was known as 'latent heat' already in the eighteenth century.

Another general fact was that on passing from solid to melt there is an abrupt change in volume. For an enormous number of solids the liquid state occupies more space than the solid state. Most important amongst the rare exceptions is, of course, ice, which is bulkier than water and therefore floats on its surface instead of sinking to the bottom. A few metals such as antimony and bismuth also expand on freezing.

But these general facts gave little help in understanding why solids melt. Major advances had to await the discovery of methods for determining the detailed arrangement of atoms and molecules in solids. By far the most general information about the structure of solids is obtained by X-ray diffraction; a number of other physical properties such as absorption spectra or electrical conductance are highly informative for certain classes of solids, but quite useless for others. In some types of solids, problems about melting are still so little resolved that effective application of any novel kind of physical measurement may still bring handsome returns.

Using X-ray diffraction, a general conclusion is that most types of solids are crystalline. Atoms in the crystal occupy regular stations in space, over millions of repetitions. Most of us are quite familiar with ordered arrangements of units in two dimensions, for example the regular arrangement of soldiers on parade. In crystalline solids such regularity is found in three dimensions; if enough units were available, the whole of space could be filled quite uniformly on the basis of any given crystal lattice, without leaving any gaps. Since this regular repetition extends over long sequences of units it is sometimes termed the *long range* ordering of atoms in crystals.

When examined by X-rays, melts of any substance show a very interesting contrast with the crystals from which they were formed. In most melts, atoms or molecules are at much the same distance from their nearest neighbours as in the crystals, but the long range order has vanished. This structural information can be tied up with thermodynamic information about the entropy of melting. The entropy of melting is calculated from the latent heat simply by dividing it by the melting temperature on the absolute scale. Theory shows that this entropy gives a quantitative measure of the decrease in order. Correlations between entropies of melting with the structural disorder aim to combine two extremely powerful modern sciences to explain why solids melt. One of these is Statistical Thermodynamics and the other the Determination of Structure.

Modern research has shown that in different kinds of solids long range order can be upset in various ways. With crystals of complex structure several disordering processes may indeed operate as distinct but simultaneous mechanism of melting. To illustrate current advances I will describe in turn four of the more common mechanisms of melting. First, all crystals undergo positional disordering. Effects of positional melting are most clearly seen in solids of simple structure such as crystals of the inert gas argon, which may be compared with a tidily packed box of oranges. On melting there is a great increase of untidiness; the space required to hold the substance increases by about fifteen per cent. Although the distance between neighbouring atoms is much the same as in

the crystals, spaces must be left empty in the melt, and rather fewer neighbours can be placed round any atom because the packing is less tidy. Compared with that tidily packed box, a loose pile of oranges would likewise take up more space. Because of positional disordering, the number of nearest neighbours, which specialists know as the co-ordination number, generally decreases on melting, but there are some significant exceptions to this rule.

The fact that the more ordered solid state is favoured at low temperatures and the more disordered molten state at high temperatures can be directly linked with the second law of thermodynamics which shows that states of matter with higher entropies are favoured at higher temperatures.

Positional disordering also explains ways in which mechanical properties of melts differ from those of the corresponding crystals. An atom or molecule moving past its neighbours can much more easily hop from one empty space to another in the more disordered liquid; such movement generally occurs so readily that most melts are obviously fluid. Significant exceptions are however known to the generalisation that a state without long range order must always be obviously fluid.

When, instead of atoms, the units in the crystal are non-spherical molecules, a second mechanism of disordering can occur on melting. If these non-spherical molecules behave as rigid lumps, these can be turned into various directions with respect to their neighbours. To obtain the closest packing in the crystal they must take advantage of any re-entrant portions, and may have to avoid sharp knobs on neighbours by being turned so as to avoid getting in one another's way.

Instead of a crate of oranges, the crystal now resembles a crate of tidily packed teacups with handles. Molecular axes of neighbours have specific orientations in many crystals. When these orientations disappear on melting, the liquid has undergone both positional and orientational disorder with respect to the crystal. Since two mechanisms of melting are operative instead of one, the total entropy of fusion is greater for such crystals than for those with only the single positional melting mechanism.

So far I have discussed both the positional and the orientational mechanisms of melting (or of disordering) as though the atoms or molecules preserved the same shape rigidly at all temperatures. An entirely new situation arises when the molecules are flexible. To grasp the new feature introduced by molecular flexibility you should think how much easier you would find it to pack rigid sticks into a tidy bundle than if you had to handle the same number of coiling and writhing live snakes and tie them into a bundle.

In quantitative scientific terms, when a molecule is described as flexible, this means that if left to itself in free space it can assume at least two and often many more alternative configurations of approximately equal energy. For example, the zig-zag skeleton of several carbon atoms in the hydrocarbon molecule normal heptane can assume the fully stretched form, as it might be of a man standing upright. By easy rotation of its parts the skeleton can also take up various crumpled configurations, like a man bending and even bunching himself up into a huddled ball. Each of these configurations has approximately equal probability of occurrence when the molecules are far apart, as in heptane vapour. However, on passing to condensed states, such as the melt or the crystals, considerations of packing as many molecules as possible into a given volume favour certain configurations and act against others. Crystallisation is an extreme instance in which only the fully stretched configuration is selected in order to fill space economically with the molecules packed side by side. Crumpled configurations also have some chance in the melt, since the greater variety of shapes achieved by introducing them increases the disorder and thus increases the entropy with respect to the crystal. A third mechanism of melting has thus become available for flexible molecules—we can count them: on passing from crystal to melt the molecules can increase in positional disorder, orientational disorder, and configurational disorder as well if they are flexible.

Detailed statistical theory reveals an important novelty for this configurational disorder of flexible molecules. However large the molecule, if it is rigid the entropy of disordering the position of

molecular centres is only about three units; but by contrast, as more and more links are added to a flexible chain the diversity of possible configurations steadily increases. The range of different configurations is so great for really large flexible systems, such as polymers, that the increase in configurational entropy on melting completely swamps contributions from all the other mechanisms. This may also apply to certain biologically important molecules related to the proteins.

The three ways of increasing disorder I have so far described tacitly assume that one can start with a regular crystal, and produce the melt simply by introducing various kinds of untidiness—a very simple and straightforward idea. Liquids whose structure can be arrived at in this way may be described as 'quasi-crystalline'. Some theories would even exclude melts containing flexible molecules from this class, and would restrict quasi-crystalline liquids to those with positional and orientational disorder only. Whatever view specialists may take about this point, recent work points to yet other types of liquids whose structure can in no way be derived merely by disordering the crystal structure. For example, requirements of long range order may obstruct certain types of ion association in ionic crystals. But these association complexes may be formed quite readily as soon as the crystals melt, because of the greater freedom.

I have described four sources of disorder which often provide reasons why solids melt, but probably these four do not exhaust all possible contributions to the entropy of melting. For example, studies of molecular movement and of optical absorption spectra point to the formation of molecular clusters of unknown structure in certain non-crystallisable liquids. I will end on a question mark since new techniques are urgently needed to give additional information about such unresolved mechanisms of melting.

Towards High Temperatures in Research

BY PROFESSOR A. R. UBBELOHDE

Within recent years, methods for achieving controlled high temperatures have multiplied. Engineering demands for materials that will withstand very high temperatures have also grown to a striking degree, in the nuclear power industry, in space rocketry, and in other directions which are at present less developed but which hold out considerable promise of future scientific and economic importance. Incentives to do research in the field of high temperatures are now very strong, though the directions in which progress is being most rapidly made are not generally well co-ordinated.

Before describing the particular researches in my own laboratories I will refer briefly to diverse possibilities, which are now available for reaching temperatures in the range 1,500°C. to 4,000°C. and even higher, but excluding nuclear reactions. Different laboratories generally have to concentrate on one or two of these several methods, because of the special skills required and the high capital cost.

Much the oldest procedure is to use solar radiation. There are stories of the use of large hexagonal mirrors of polished bronze or brass to burn enemy fleets by Archimedes in the third century B.C. It is difficult to establish accurate information about the sizes of early solar furnaces. Obviously the catchment area of the mirrors used determines the total power which can be concentrated in any solar furnace. Recent advances in France include catchment surfaces more than 30 feet in diameter. Peak temperatures of around 3,000° C. are readily maintained in the hot focus. An awkward requirement is that solar furnaces must be easily moved to remain in the most favourable direction towards the sun. Their location is also limited by considerations of climate and geography.

Other more adaptable ways of attaining very high temperatures are often much more costly to install, but more flexible in use.

Furnaces in which heat is generated by ordinary combustion of gaseous or solid fuels generally have an upper limit of operation which is too low for work at very high temperatures. Chemical reactions which liberate heat tend to go in the reverse direction at sufficiently high temperatures, following a general thermodynamic rule first recognised by Le Chatelier. Possibly high-cost fuels such as vaporised aluminium or magnesium will find some use eventually, since the upper limit or temperatures as given by dissociation of the oxides of these metals is considerably higher than for conventional fuels.

A group of thermo-mechanical methods which we are studying in various ways at Imperial College is concerned with the transient but extremely high temperatures reached in shock or detonation waves. Shock waves are merely sound waves of extremely high intensity, and can be generated in a suitable gas by sudden mechanical impact, sudden release of electrical energy, or sudden release of chemical energy from explosives. In certain gases, such as xenon, peak temperatures have been claimed well over 20,000° C.

It must be noted that the narrow zone of shock or detonation in the gas travels quite fast through the medium. Behind the shock zone the gas cools down again quickly so that no part of it remains at peak temperatures for more than perhaps one ten-thousandth part of a second. Though transient, such high temperatures are extremely useful in certain forms of high temperature research. For example, if we add small amounts of other substances to the gas traversed by the shock wave these are heated very rapidly to extremely high temperatures and are then cooled down again almost as rapidly. When solids are formed at these peak temperatures, rapid cooling serves to freeze-in structures that normally occur only at high temperatures, thus permitting their study and use under ordinary laboratory conditions.

In another broad group of methods, we can generate extremely high temperatures by contriving the electrical acceleration of

charged particles, which are then braked in some way so as to liberate their kinetic energy again in a very small volume as heat. The oldest version of this general method has been utilised for many years in resistor furnaces, which have as their humble cousins the electric cooker and electric heater used in millions of homes. In a resistor furnace the first requirement is a solid conductor across the ends of which voltage is applied. To operate such furnaces at very high temperatures the conductor obviously must not melt. This has favoured the choice of graphite as a resistor material, since this solid does not melt till about 3,700° C. Polycrystalline graphite is comparatively cheap, but it has certain mechanical and other disadvantages.

A recent development studied in our laboratories offers a number of important advantages for the attainment and control of the highest temperatures. It utilises resistors with a marked directional difference of properties, for example, parallel and perpendicular to the furnace walls. We can now fabricate tubes and other shapes from well-orientated graphite crystals in which the anisotropy of properties parallel and perpendicular to the carbon hexagon networks is almost as marked as in perfect single crystals. With such well-orientated graphite the thermal conductivity parallel to these networks proves to be even higher than that of copper. However, at right angles to them, the thermal conductivity may be less than one two-hundredth part of that of copper.

One novel construction of furnaces for very high temperatures takes advantage of this low thermal conductivity in one direction, using a tube of well-orientated graphite heated by passing an electric current with its outermost surface at only 2,000° C. and its inner surface as high as 3,400° C. This onion skin principle of construction, with all the carbon networks of the crystals arranged parallel to the surface, makes the maintenance and control of very high temperatures much more economical.

Resistor furnaces for use at the highest temperatures have, however, the awkward feature that electric current must be supplied by massive electrodes in contact with the resistor. One rather expensive but very convenient way of avoiding the need

for electrodes is to generate fluctuating electromagnetic fields so that induced currents are set up in the solid resistor. By this means we have constructed induction furnaces using well-orientated graphite and the onion skin design to permit operations up to 3,500° C. When the chemical reactions to be studied at these high temperatures call for careful control of purity and of quenching rates, induction heating offers outstanding advantages which justify the costly and rather cumbersome generators required.

Yet another group of methods of attaining very high temperatures has evolved from experience with electric-arc formation in gases or vapours. Arc furnaces in their older forms have been utilised for many years. Quite generally, ions may be generated in various ways in the gas and may then be accelerated by applying an electric voltage. Collisions between such fast-moving charged particles and other molecules liberate their energy as heat and rapidly raise the whole gaseous mass to very high temperatures.

In such methods the electrical energy injected into the gas is not limited by the chemical energy of any reactions which may take place, and in principle extremely high temperatures can be reached. These ion plasma methods, as they are called, are more readily adapted to reaching sustained high temperatures than the shock waves mentioned above, but cooling tends to be less rapid.

I have described a few of the more novel methods of working at very high temperatures in some detail, because experience shows that the provision of novel and convenient methods of experimentation soon stirs up curiosity and enterprise to attack new problems in research. In due course industrial applications may follow.

In the previous chapter I described some of our researches on melting. These are relevant to one line of progress concerned with solids which can be exposed to extremely high temperatures before they melt.

High melting points are usually found in solid structures in which the atoms are very strongly bonded together, and for which there is only a single melting mechanism. Polyvalent elements include solids such as carbon with a melting point of about 3,700° C., and tungsten with a melting point of 3,370° C.

Related crystal structures which contain two dissimilar atoms include nitrides of titanium and tantalum, both melting just below 3,000° C., borides of tungsten and zirconium, melting somewhat higher, and certain carbides which show some of the highest melting points yet discovered for solids.

Because of these very high melting points, many of these solids are difficult to purify and may not even yet be known as coherent polycrystalline masses. To some extent the difficulty in fabricating solids of very high melting points in compact form is being overcome by sintering powders, sometimes combined with mechanical rolling or hammering whilst they are hot. Direct melting and crystallisation is however more satisfactory for some purposes.

High melting points normally go together with extreme mechanical hardness; applications as cutting tools and for durable mechanical bearings have already attracted much technological research to this field. Other applications as materials extremely resistant to chemical attack at high temperatures are also being studied. Single crystals of such new materials may actually be much rarer than diamonds of comparable size, but whether any of these solids will ever become fashionable with ladies as jewellery remains to be seen.

From the previous chapter you will realise that the molten states of these substances also present liquid structures that are of great scientific interest. Novel possibilities can be seen just beyond the present frontiers of knowledge, and much additional research in the region of high temperatures can be confidently predicted in the years ahead.

Man-made Conductors of Electricity

BY PROFESSOR A. R. UBBELOHDE

When Michael Faraday began to examine the electrical properties of solids, more than 130 years ago, he found that many familiar substances such as sealing wax and rubber oppose extremely high resistance to the flow of electric currents. Other solids which readily allow electricity to flow through them were termed conductors. More than two-thirds of the natural elements exist as metallic solids. Many of these metallic elements alloy with one another fairly readily so that mixed metallic structures can be made in great variety. Because of this property of good conduction for electricity, a great body of scientific information and enormous organisations have been built up around the electrical properties of metals. To understand their importance you have only to look around you and to think of the great variety of roles played by electricity in modern technology and modern civilisation.

Here I want to describe researches on synthetic good conductors of electricity which do *not* start with the atoms of metallic elements, but instead aim to use other atoms normally regarded as non-metallic. The basic property to be investigated is the flow of electric charge when a difference of electrical potential is applied to opposite ends of a conductor. After the discovery of the electron, which is the atom of electricity, it was at first thought that the flow of charge in a conducting solid was much the same as the flow of water molecules down a pipe when a head of pressure is applied at one end. However, application of quantum theory led to the rather surprising conclusion that intense movements must be attributed to the electrons in all solids, whether they are conductors or insulators.

For an electric current to flow there must be a net drift of charge in one direction when a potential is applied. This drift

process is rather like that of a group of friends immobilised in one of the large crowds so familiar at public events. If these friends all have to get away urgently to the same party, each of them will strive to accelerate independently towards the exit; although their movements will tend to be neutralised by collisions with others in the crowd, moving in opposite directions, their common incentive activates them again and again towards the exit, and results in a current in that direction.

Modern quantum theory of electrical conduction has shown that to attain high electrical conductivity, a fairly large fraction of the electrons in a solid, of the order of one electron per atom, must be capable of easy and repeated activation. Repeated collisions with the framework of the atoms in which these electrons move soon wipes out the acceleration in one direction imparted to any electron by the applied potential difference.

On this basis, the physical prescription for a good conductor is a solid in which the electrons have a range of energies with many vacant energy levels only slightly above those already occupied. In good conductors, carriers of electricity are repeatedly activated up to these vacant energy levels; although they are soon knocked down again by collisions with the atoms of the solid, a net drift of charge will result. This decisive range of energy levels that determines the behaviour of the electrons in a solid is usually known as an energy-band. The presence of many vacant levels only just higher than those normally occupied means that an energy-band in a good conductor is only partly filled by electrons.

All metals found in nature and their conducting alloys have at least one partly empty band of energies which permits conduction. Our research problem was to discover whether any non-metallic elements can be put together so as to give solids with partly filled energy-bands, and thus to make synthetic good conductors of electricity. One avenue of development depends on the application of very high pressures to certain insulating solids. Under sufficient compression energy levels available for the electrons may overlap sufficiently to give partly empty bands. For example with elemental red phosphorus metallic conduction has been reported at pressures of about a hundred thousand atmospheres. However,

the equipment for such high pressure is costly and the outcome at present rather uncertain.

Much wider opportunities appear to be presented by the electrons in organic molecules whose bond systems are conjugated, or contain aromatic rings. Organic chemists have long known that in chemical reactions effects of attack on the electrons at one end of even a large conjugated system of carbon atoms are readily transmitted to the other extreme end, through the mobile electrons in such molecules.

My own interest in applying this mobility to yield new solids with metallic conduction dates from 1933, when X-ray crystallographers showed that the dimensions of the carbon skeleton in the very simple aromatic molecule naphthalene were practically the same as those in the giant network of carbon atoms in graphite. Even at that time, it seemed likely that conduction of electricity which can be observed in graphite was somehow linked with the mobility of electrons in aromatic molecules. Our problem was by what means to connect one molecule to the next, so as to construct molecular networks through which electrical conduction extends from one end of a solid to the other as with metals.

By 1947 mathematical calculation of electron energy levels in aromatic molecules and in graphite reached sufficiently clear conclusions to permit the next step forward. These calculations showed that in graphite an empty band of energy levels must lie only just above the band which is fully occupied by electrons.

This tantalising situation suggested that if only it were possible to inject electrons artificially so as to partly fill this empty band, the solid would at once conduct electricity like a metal. As a slightly more subtle alternative, if only a proportion of the electrons could be sucked away from the full band, again a solid with a partly filled band and good metallic conduction ought to ensue. You must remember that crystallography had already shown in 1933 that graphite can be regarded as a stack of giant aromatic molecules parallel to one another. In this connection organic chemistry again gave the clue for methods for injecting electrons or sucking away electrons from these giant aromatic molecules.

The most generally successful method we have used is to

prepare various layer compounds of graphite. Layer crystals form quite readily when graphite is merely exposed to various electron accepting molecules such as bromine or iodine monochloride. Under these conditions the giant parallel networks of carbon hexagons separate spontaneously and the additive forms layers between them. The resulting crystal structure closely resembles an enormous pile of sandwiches.

Somewhat more difficult to prepare but quite as important are similar sandwich compounds between graphite and electron donor atoms such as potassium, rubidium or caesium. These particular crystal compounds are chemically more reactive and have to be prepared in complete absence of air or moisture, at temperatures around 400° C.

With reference to these giant layer systems my expectation based on other facts of organic chemistry was that the electron donor atoms would inject electrons into the empty bands of the graphite molecules between which they lie in the sandwich pile. Similarly, contact with electron acceptor atoms should suck electrons away from the full bands.

This expectation was soon realised in a dramatic way; we found that graphite shows a very large increase in electrical conductivity when exposed even to bromine vapour, an experiment which lends itself to easy demonstration. Detailed measurements of the electrical conductivity and of other electronic properties of sandwich compounds between graphite and various types of additive, both electron acceptors and electron donors, have confirmed that these solids really do constitute a new class of good conductors of electricity, at least comparable with that of metallic nickel and probably even better.

As always with new discoveries in science, enticing avenues for research and new problems become evident almost simultaneously. I will describe two of these with the reminder that we really are at the frontiers of knowledge and cannot always foresee what lies beyond.

The first problem refers to what is technically known as the directional anisotropy of properties. Thinking again of the layer structure of a giant pile of sandwiches, electrical and physical

properties are likely to be very different in directions parallel with the layers, or in the direction crossing the layers. Pronounced directional differences are in fact observed with the parent graphite, and also with various good conductors of electricity prepared from it as sandwich compounds. Parallel with the layers, electrical conductivities are uniformly high. Across the layers different sandwich fillings yield widely different behaviour. This marked anisotropy may have some very important technical applications. For example, one interesting device we have investigated could eventually have possibilities for the direct generation of electric power from heat, without turbines. It utilises the fact that the thermo-electric power of graphite and of the sandwich compounds derived from it is quite different in the two principal directions parallel and across the layers. Instead of utilising the conventional pair of metals, thermo-electric couples have now been constructed from a single substance, making use of this anisotropy.

To advance these researches, a second problem is to prepare really large single crystals of graphite before making the sandwich compounds from them. Crystal imperfections and boundaries between crystallites scatter charge carriers moving through the solids, and this scattering needs to be controlled with high accuracy for certain modern electronic applications.

Methods for growing large single crystals of metals have, of course, long been known. With graphite, one obstacle to growing large perfect crystals is its very high melting point which, as I previously mentioned, is about 3,700° C. This conclusion serves to emphasise how advances at one frontier of science may suddenly remove obstructions in quite different directions not always foreseen by the unwary. By describing some of my researches on why solids melt, on the attainment of high temperatures and on the synthesis of good conductors of electricity, I have tried to give a kind of impressionistic picture of this interdependence of advances in knowledge at different parts of the frontiers.

The Coming of Modern Plastics

BY PROFESSOR C. E. H. BAWN

The term 'plastics' is now a household word and you will all be familiar with plastics in one form or another. From the telephone to the television cabinet, from dentures to spectacles and from fibres to packaging materials plastics have become part of our modern civilisation. It would be hard to imagine a world without them, yet to go back only twenty years would deprive us of the majority of the plastics which today are so familiar.

The many different and commonly used materials now made from plastics vary from adhesives to coating and sheeting materials, rubbers, rigid mouldings, or synthetic fibres, and provide a greater variety than found in all metals, woods, and natural fabrics. The new materials are to most people familiar in their final form and are not normally thought of as chemicals. But they are in fact all derived from natural or synthetic chemical products which usually have a special processing to go through before they reach their final form. The recent growth of their development and application is one of the most spectacular achievements of twentieth-century science and industry.

Plastics are members of a class of chemicals known as 'high polymers'. The most remarkable properties of these substances, and the ones which differentiate them from all other types of chemical, are their strength, toughness, elasticity, hardness and deformability, which are generally referred to as mechanical properties. To understand the origin of these particular attributes and their manifold uses it is necessary first to understand the nature and constitution of these substances. In spite of their recent development there is nothing new about high polymers. They are among the oldest and most familiar materials and in one form or another have been used to feed, clothe and house mankind from the earliest recorded times. Cellulose, the carbohydrate that one meets in everyday use in the form of cotton, paper, rayon and numerous plastics and which is the most abundant material

in the vegetable world, is a polymer. So are the protein materials, wool, silk, casein, leather and gelatin. Although they have been used for over 6,000 years the nature of these substances remained largely a mystery to the chemist until the turn of the present century. The recent remarkable and spectacular progress in the development of new plastics is a result of chemical research into their fundamental constitution.

Before we examine the details of their chemical nature it is worth-while to reflect for a short time on the history of the developments which have occurred largely within the past quarter of a century and within the lifetime of many of us, and to try to understand why these developments were long delayed.

Over the past century chemists have examined, synthesised and characterised hundreds of thousands of substances. These have given birth to the many products, dyestuffs, drugs, perfumes, and fuels, for example, so necessary to our modern civilisation. These substances are comparatively simple members of the organic family, and the more complex ones such as the natural high polymers, like cellulose, the proteins and the starches got little attention from the organic chemists. The same was true of the resins, and other waxy or gluey messes encountered frequently in organic chemistry.

The growth of the newer branch of chemistry—known as physical chemistry—towards the end of the nineteenth century and the early part of this century led to the recognition of the three states of matter—solid, liquid and gas—and most of the simple compounds of inorganic and organic chemistry fitted perfectly this simple classification. This scheme, however, ignored many of the naturally occurring materials and resins I have mentioned. In any case organic chemistry was so full of other interesting problems that these resinous substances which were so difficult to handle were passed over for the time being.

Nevertheless, the naturally occurring substances like cellulose proteins and rubber had not been entirely neglected, and in the 1920s it was first realised that these substances were composed of large molecules—enormous in size compared with numerous organic substances which had already been fully characterised—

and that each of the molecules was made up of a large number of building blocks. Chemists began to call these substances poly-something and this is the basis of the present general terminology for this class of compound.

The simple substance which served as the building block was called the 'monomer' and the polymer—many mers or many parts—is formed by a combination of many such units. Progress in unravelling the true nature of these substances was delayed because the then-used methods of study of substances were inadequate. The difficulty however was only temporary and new inspiration and techniques soon revealed the true nature and general pattern of the formation of the giant molecules. The answer which came out was relatively simple—high polymers were built up by the linking of monomer units end-to-end in chains—usually many thousands of units long—just as a metal chain is made by forging the links together.

Once the general pattern had been established the chemical methods of synthesis of polymers by joining together simple units in the form of a chain structure was soon discovered. It was the acceptance of this hypothesis some twenty-five years ago which dictated the trend of research and was the factor largely responsible for the phenomenal progress in polymer science, and which laid the foundation of the plastics industry as we know it today.

When one recalls that the first truly synthetic fibre, nylon, was introduced only twenty years ago and that polyethylene was discovered as recently as 1937, it is amazing how rapidly plastics have become essential to, and part of, our modern civilisation.

Once the principles governing the synthesis of high polymers were established new and exciting prospects resulted from the creative power made possible by this increased knowledge. The invention of new kinds of plastics and fibres became a practical possibility and this impetus is still gathering speed with the discovery of new methods of joining the building blocks together. This is the stage we have now reached in polymer chemistry. Starting from a need for some material of specified properties we are in a position to create a new material tailored to fill that need.

As building stones, industry uses some fifty units (monomers)

largely derived from coal and oil. The simplest of these monomers is ethylene which is a product of oil cracking. Ethylene consists of two carbon atoms to each of which are attached two hydrogen atoms, CH_2-CH_2. Now imagine a very large number of the carbon atoms to be linked together to form a chain; the molecules so synthesised, and which have a backbone of carbon atoms flanked with hydrogen atoms, are known as polyethylene, or polythene. They are very familiar to you as a film used in packaging and moulded articles such as plastic bottles, washing-up bowls, buckets and toys.

The process by which the small ethylene molecules are joined together is analogous to the making of a very long pearl necklace by adding pearls one at a time to the growing chain and in practice is accomplished by heating ethylene at high temperature and pressure in the presence of a little oxygen. The oxygen initiates a chain reaction in which the monomer molecules are attached successively to the growing chain. Catalysts other than oxygen have been discovered recently which enables the ethylene polymerisation reaction to be carried out under ordinary conditions of temperature and pressure.

In general the process of polymerisation is the synthesis of long linear structures by either a chain reaction or by a series of successive chemical reactions. A wide variety of agents have been discovered which initiate and control these reactions.

Scientifically, polyethylene is one of the most interesting of all the giant molecules. It is made of the simplest of building blocks—the basic hydrocarbon unit CH_2—and chemists have been able to correlate polyethylene properties with its molecular structure very satisfactorily. In fact, ethylene and its polymers has served as a model for experiments and deductions that led to understanding of more complicated polymers.

If some of the hydrogen atoms on the backbone are replaced by other kinds of atoms or groups then new kinds of polymers result. Thus if one of the hydrogen atoms on alternate carbon atoms of the CH_2 chain is replaced by a chlorine atom then the repeating unit is not CH_2-CH_2 but CH_2-$CHCl$. This polymer is familiar to you as polyvinyl chloride—p.v.c.—used in making

plastic curtains, upholstery covers, coating wires for insulation and for floor coverings.

If the substituted atom is a cyanide group CN instead of chlorine then the polymer formed is the well-known fibre—acrylonitrile—sold under the trade names of Orlon, Courtelle, and in slightly modified form, as Acrilan. Many of the common plastics are based on this simple molecular structure in which one or both of the hydrogen atoms in the hydrocarbon chain of polyethylene are replaced by other atoms or groups. The simple exchange of atoms in this way, which only modifies the nature of the atom sheath around the long carbon backbone chain, gives products which show properties varying from strong fibres to plastics or rubbers.

So far I have mentioned only the simplest kind of polymer obtained by polymerising a single monomer—ethylene to polyethylene, styrene to the glass-like polystyrene, acrylonitrile to polyacrylonitrile. It is obvious, however, that if we started with not one monomer but a mixture of two monomers then we should synthesise a chain containing units of each of the monomers—our pearl necklace would now have black and yellow beads and not one type only. This kind of molecule is known as a copolymer, and copolymerisation gives a further means of modifying and controlling the properties of the final polymer. Thus if a polymer made from a single monomer is too hard for processing it may be softened by copolymerising a small amount of the second monomer with it, or vice versa. One of the best-known synthetic rubbers—first made in the U.S.A. during the war because of the shortage of natural rubber—is a copolymer of the hydrocarbons styrene and butadiene.

Lastly, I should like to mention another simple polymer which has only recently been made, because this new synthesis has become of immense importance and has opened the way to immense scientific and technological developments.

Referring once again to our prototype polymer polyethylene—which you will remember is a chain of CH_2 groups—then instead of replacing each alternate atom of the hydrogen by chloride or CN let us replace the alternate hydrogen by the grouping CH_3—

that is, a carbon atom to which is attached three hydrogen atoms. That is, the repeating unit in the chain is—CH_2-$CH(CH_3)$—two carbons in the backbone and one as a branch. This polymer has the structure of polypropylene. The new polymer, which was discovered only four years ago, has resulted in a major break-through in the synthesis of high polymers and has opened up new means of synthesising plastics.

How to Classify at the Borderline of Life

BY DR. P. D. COOPER

Viruses represent a New Frontier in Biology today because we have only recently been able to study them as closely as animals and plants have been studied in the past. In addition to their effects on mankind, viruses are interesting because they are simple models which tell us something about those pieces of heredity called genes, and more particularly about what genes do.

I shall go on to say something about how one might classify viruses, but first, why take up this intellectual challenge? Well—because viruses are there; but another reason is that rules help understanding. We may groan at a grammar book, but it does help in learning a language, and virologists at the moment would particularly value a classification that really works, because new information is coming in confusingly fast. We should like the right mental pigeon holes for this new information; we should like it even more if we could see important general patterns which we cannot see at the moment, because these patterns would help solve the wider problems of genetic function and of how the cell controls its own metabolism.

I should mention that all viruses are already grouped into: first, those which infect bacteria; second, those which infect plants; and third, those which infect animals. These divisions follow the three main groupings of living things and amount to a partial classification; I shall return to this later, but most of my remarks will apply to the further classification of animal viruses only, including the viruses of the human animal.

Earlier systems of classification have naturally relied on the information available at the time. Now viruses are very small things indeed, they are hidden by an excess of chemically similar substances, they are difficult to grow because they need living cells to grow in, and they are all but invisible in the best of optical

microscopes. Thus it has not been easy to study the virus itself, but in contrast it was easy to study the effects of the virus, namely the type of illness caused, the type and locality of the local damage, and the animals which are made victims or carriers. Thus it is not surprising that early classifications were based upon such criteria which, unfortunately, more recent work has shown to be quite unsuitable. For example, chicken-pox and shingles, although apparently different diseases, nevertheless are caused by the same virus; foot-and-mouth and cow-pox are somewhat similar diseases of the same animal but are caused by viruses which are as different in shape, size and substance as viruses can be. Myxomatosis and yellow fever viruses are both carried by mosquitoes, but are also quite distinct.

This type of classification is actually based on the environment that the virus selects, and *habitat* as a criterion turns out to be as unreliable for classification of viruses as it is for animals; clearly, not all creatures in the sea are fish, and not all fish are found in the sea.

There is another difficulty: all biological groupings depend upon criteria which are not easily changed by simple mutation, that is to say by a small hereditary change. One would not classify giraffes and goats separately, for example, if mutant goats often turn up with extremely long necks and looking like giraffes. Now viruses are much smaller and therefore simpler than goats, and a single mutation or change in the genes will have more effect, in proportion to other characters, on viruses than on goats.

Furthermore viruses grow much more rapidly than goats; many viral generations occur in one day, so that viruses appear to be in a state of rapid genetic flux, when judged by human time scales. For this reason, it happens that viruses can mutate and thereby change their habitat very easily, so that, for example, certain forms of poliomyelitis virus can rapidly change from a safe virus, which lives purely in the human intestine, into a dangerous one which also attacks the human nervous system.

Thus we need criteria which are not easily changed by mutation, and habitat is not sufficiently stable or exclusive. What then shall we use? Fortunately the methods of growing, handling, measuring,

analysing, counting and viewing viruses have all improved enormously in the last decade, and we now know much more about the virus particles themselves.

We can in fact now classify viruses like animals and plants, that is by the structure of the individual organism. In our case the organism is the virus particle, but viruses are so small that they are intermediate in size and nature between living things and single chemical molecules, and when one examines the fine structure of viruses one has to turn to chemical composition. There are several aspects of their chemical make-up which could be selected; one might indeed feed all the known data into a computer and let the machine make the classification, but it would be more satisfying to pick one or two criteria which seem pre-eminent. If we choose correctly, the computer should give the same results, and will provide a cross-check.

Fortunately, two stable and outstanding criteria exist. The first depends on whether the genetic code is carried by ribonucleic acid (RNA) or by deoxyribonucleic acid (DNA). It must be one or the other, and cross-mutation is inconceivable, although RNA and DNA may not differ in function in viruses as fundamentally as in larger organisms. Another question for further work is whether the same information may be carried as a code by both DNA and RNA, thus providing two phases for the one virus.

The second criterion for classification is the content of essential fatty components or lipids. Some viruses contain lipids which cannot be removed without killing them, but others do not, or the lipids are not essential for infectivity. This criterion seems a little arbitrary but in practice is quite a good one. One can easily test for essential lipid by the reaction of the virus to ether or detergents, and lipid is related to the growth of many viruses, in an important way, which we do not yet understand. At the moment it seems that, unlike the fat-free viruses, the fat-containing viruses cannot make protein molecules which bind together to make a rigid basket-like cover for the virus nucleic acid; instead the fatty viruses seem to rely on the lipid-containing wall of the cell itself to donate a loose bag to protect the nucleic acid.

We thus have two criteria: one, content of DNA or RNA;

two, content or not of essential lipid. These two dividing lines give four groups of viruses, and, if one arranges the viruses in each group in order of decreasing size, a considerable degree of order results. The viruses often fall together in groups which produce similar antigenic proteins, and this is a good indication of close relationship. These last two factors (size and antigenic content) incidentally give us an extra two chemical factors for our classification.

A certain group of very large and complex viruses, which includes those that cause small-pox, cow-pox and myxomatosis, have to be given a separate place in this scheme. They are probably intermediate between the smaller viruses and certain larger organisms which cause trachoma and typhus; these larger entities are themselves like degenerate bacteria.

When we examine this pox-group and the four other groups separated by chemical criteria, we find that several biological properties are separated also; thus the members of each chemical group have unique biological properties in common, which encourages the thought that the chemical criteria mean something in biological terms. Interestingly enough, these biological properties sometimes include habitat. Thus, when the exceptions are removed by a preliminary chemical sorting, certain habitats are seen to be related to structure, one example being certain viruses which grow in both insects and mammals, and which are known as the 'arthropod-borne' viruses.

Now, one further thought. Despite my not liking classifications based on habitat, you may have noticed that I have quietly accepted the initial division of all viruses into parasites of animals, plants or bacteria. However, this division also depends on habitat. You may well ask, why not abolish these divisions too and apply purely structural criteria to all viruses? Why not, indeed; the cellular metabolism used by all viruses is very similar in all living things, and many plant and animal, and some bacterial, viruses are almost indistinguishable in structure. Some plant viruses will also grow in insects, which are after all animals in our definition.

I think that many virologists would hesitate to accept this

final iconoclasm, and for the present I should hesitate, too. I hope in fact that one result of suggesting this classification will be either to break down such subdivisions if they are artificial, or alternatively to stimulate the providing of solid evidence for the difference of the three groups; this last might amount to information of quite fundamental importance for biology.

How Living Organisms Regulate Their Metabolism

BY PROFESSOR SIR HANS KREBS

One of the most characteristic features of all living organisms, from the simplest bacteria to the most highly developed animals, is their ability to adapt themselves to changing circumstances. For example, they can subsist on a great variety of different foods and the amounts of food they take up are, as a rule, carefully adjusted to their needs; there is generally no over-eating or under-eating. When an animal is exercised and more energy is needed, more food is taken up and more is converted to energy. When water is lost, by perspiration, for instance, various regulatory mechanisms in the body see to it that more fluid is taken up.

The existence of such adaptations is common knowledge. To the biologist they present the problem of finding out the kind of mechanism by which they operate. Thanks to the progress of biochemistry answers to this question are now within reach. While earlier biologists had to be content with a mere description of such adaptations, we have now the tools to explore their mode of operation.

It is the object of biochemistry to study the chemical reactions occurring in living cells. Living organisms represent intricate systems of numerous chemical substances which continually react with each other. All manifestations of life, including even those of the mind, have a material, that is a chemical, substratum, and we believe that life is not only accompanied by chemical changes, but that these chemical reactions are in fact the backbone of all manifestations of life itself.

To the biochemist, then, one of the most challenging problems is this: what is the chemical nature of the systems which underlie the capacity of living organisms to adjust themselves to changing needs? Much progress has been made in recent years in the study of these automatic control mechanisms and I would like to talk

about some aspects of this development today. My examples are taken from the field of metabolism. This term, metabolism, refers to the major chemical activities of living organisms, and among these major activities two kinds stand out: first, there are the reactions which synthesise cell constituents; and second, there are those which supply energy.

Let me first discuss the automatic control of the reactions which lead to the synthesis of cell constituents. Living organisms constantly build up new cell material. This is obvious when organisms grow, but it also occurs in non-growing tissue because all active tissues, such as liver, or kidney, or muscle, have a continuous wear and tear which must be replaced. Now, replacement of wear and tear in man-made machines, such as a motor car, is usually in terms of pieces of the machinery, say, tyres, brake shoes, gear components, etc. In living organisms wear and tear and replacement is in terms of chemical substances. Thus replacement or, in the case of growing cells, the manufacture of new cell materials, means obtaining a set of special chemicals from the food.

There are about 50 different basic simple chemicals—no more—which are required by living cells. They are the same for all types of cells. They are the 20 or so amino acids, two pruine bases, two pyridimine bases, a few sugars, a number of fats and fat-like substances such as cholesterol, a few porphyrins for the red blood pigment and respiratory catalysts, about half a dozen components for coenzymes, and so on. These chemicals are required in definite quantities varying from substance to substance, just as in building a house each category of the building materials—bricks, mortar, tiles, window frames, doors, plumbing components, etc.—is required in definite quantities and at the right moment.

There are two sources of supply for the basic chemicals. Either they come directly from the food, ready-made, or they are manufactured from the substances contained in the food. In higher organisms quite a few substances—the vitamins, and the ten so-called essential amino acids—cannot be manufactured in the body, but must be provided by the food. All other organic

substances can be synthesised in the organism, given suitable starting materials. Some micro-organisms even synthesise the essential amino acids and the vitamins, as do plants. How does a living organism control the rate and the quantity of the required supply?

Experience shows that when sufficient quantities of a building material are present in the food, for instance of the non-essential amino acids, or of cholesterol, then the organism does not make it. The remarkable thing is that the enzymes capable of making these substances and the potential starting materials are all there. Yet the syntheses do not take place, and the potential starting materials are used for other purposes. Usually they are burned to supply energy, or they are stored as reserve materials. What, then, prevents the cells from synthesising and accumulating chemicals which they do not need?

A principle has come to light within the last few years which explains at least in some cases (but which, in all probability, holds very widely) how the synthesis of cell constituents is regulated. The synthesis is prevented by the final product of the synthesis itself. This type of synthesis usually involves many steps, and each step requires a specific enzyme. It is the first step which in these cases is stopped because the final product inhibits the enzyme catalysing this step. In fact, the nature of control is of the type referred to by engineers as 'negative feedback'. It is analogous to many devices used in simple physical apparatus and especially by electronic engineers. A simple example is the thermo-regulator controlling the temperature of a hot water tank or of a room. When the temperature of the water tank or a room has reached the desired level, the source of the heat—an electric current or gas heater—is automatically cut off, usually by expansion of a metal or a liquid, and when the temperature falls the supply is automatically restored. Analogously, the accumulation of a cell constituent stops the additional synthesis of this substance, and when the constituent has been used up in further reactions the inhibition of the synthesis is abolished and production is resumed.

It is thus possible to account for the control of the supply of chemicals by an entirely mechanistic device, although at first

sight this control mechanism appears to be the result of a purposeful and intelligent decision.

Let me now turn to control mechanisms in another sphere of cell metabolism, that of energy supply. The need for energy in higher organisms is well known to vary with the state of the organism. You are familiar with the fact that the harder we work physically the more energy we need and that we obtain this energy mainly by the combustion of foodstuff. During physical exercise, then, more food is burned than while at rest. The burning of food requires specific catalysts and in the state of rest these catalysts obviously do not work at full capacity. We have here the same situation as in the case of the synthesis of cell constituents when these constituents are amply present in the food: although the catalysts and the materials which react with them are present, the reactions do not take place. Something stops these reactions from taking place until they are wanted.

We have learnt a good deal in recent years about the way the transformations of energy in living matter are organised and we know that food cannot be used directly to drive the machinery of the cells and tissues. The energy set free in the degradation of food must first be converted into a special kind of chemical energy before it can do work. This special form of chemical energy is that stored in the pyrophosphate bonds of adenosine triphosphate (often referred to as ATP) and is released when these bonds are hydrolysed. Adenosine triphosphate is the immediate fuel of living cells.

When the muscles rest, they build up a store of adenosine triphosphate and when the muscle contracts one phosphate group is split off from each molecule of ATP to form adenosine diphosphate and inorganic phosphate. The combustion of food subsequently provides the energy for the re-synthesis of adenosine triphosphate from adenosine diphosphate and phosphate, and the combustion of food is so organised that it cannot take place unless it is coupled with the synthesis of adenosine triphosphate: it depends on the presence of adenosine diphosphate and phosphate.

When the muscle is at rest and no energy is required, the available adenosine diphosphate will soon be converted into

triphosphate whilst foodstuff is burnt. Because of the obligatory coupling between combustion and adenosine triphosphate synthesis the process of combustion will slow down when the level of adenosine diphosphate has fallen. Thus immediately after exercise—that is, during the recovery period—the rate of combustion is high and it falls to low levels when the stores of adenosine triphosphate have been replenished. As soon as the muscle starts to work again adenosine diphosphate will become available for reconversion to adenosine triphosphate and the rate of combustion will therefore increase.

These considerations indicate that the controlling mechanism here is again of the feedback type. The expenditure of energy, that is the fission of adenosine triphosphate, automatically causes a rise in the level of adenosine diphosphate and inorganic phosphate, a condition which stimulates combustion.

This mechanism is probably one of the major ones concerned with the control of energy supply in all types of cells. There are others as well and a great deal more has still to be learnt about all the mechanisms which control the activities of living tissues.

From the theoretical point of view the recent developments represent a real advance, inasmuch as we have begun to understand complex behaviour in terms of chemical systems. This beginning opens up wide fields for further investigations. There are perhaps no immediate opportunities of applying the newer knowledge to the practical problems of medicine and agriculture, but I am confident that, sooner or later, this development will bear fruit on practical issues. One of the outstanding problems of medicine—that of the nature of cancer—can in fact be looked upon as a problem of control of cellular activities. Cancer cells are cells out of control. Their growth is no longer co-ordinated to the needs of the organism. As yet we know nothing of the reasons responsible for this loss of control, but it is reasonable to hope that further studies of the normal biological control mechanisms of the kind I have discussed may throw light on the nature of cancer.

Biological Clocks

BY PROFESSOR G. P. WELLS

How do living things know what time of day it is? That is a much more complicated problem than you might perhaps suppose. And for reasons which I will try to explain, a number of biologists are trying to solve it today.

Everybody knows, of course, that some animals are more active by day and others by night—in fact, there is probably no animal, and no plant, whose life continues quite uniformly and steadily all round the clock. Everything is affected to some extent by the changes in light, in temperature, and so on, which result from the fact that we live on a spinning globe.

One might suppose that the daily rhythms of living things are due to the direct action of the environment on the organism. One could reason like this. It is well known that temperature affects the speed of most biological processes. Again, some animals are excited, and others are inhibited, by light. And, of course, the whole metabolism of a green plant is different by day and by night—it must be—for only in light can the plant build up new living material, out of the simpler molecules that it sucks up through its roots, and breathes in through its leaves. So, in one way or another, we expect the alternation of day and night to impose variations in activity on the organism.

That is very true, but to suppose that that is the whole story would be to miss the most interesting part.

For the real problem lies in this fact: that in many organisms—certainly in the great majority of animals and plants, and perhaps in all of them—there are what we call biological clocks. A biological clock is something inside the animal or plant, something not directly dependent on the changes in the environment, which tells its possessor what time of day it is. It enables its possessor to anticipate the rhythmic changes in the environment, and prepare to meet them.

After all, we know that from our own experience. We have, so

to speak, an inbuilt sense of time and, in fact, all of our physiological processes change with the time of day. Our pulse rate, our kidney action, our body temperatures—these all show diurnal rhythms, and the rhythms are by no means simple reflexes to the changes in our surroundings. Biologists have tested this by subjecting themselves to perfectly uniform conditions. They have even gone down into a deep mine, for example, where temperature, illumination and everything else were perfectly constant—and still their physiological rhythms persisted for many days.

Those who work on fast ocean liners, the ones which run between Europe and America, know very well that the passengers tend to go to bed early, and get up early, on the westward passage, but late on the eastward. This is because the length of the day—the time between one sunrise and the next—is changed if you sail round the world. You have to keep re-setting your watch. The day is about 45 minutes longer on the westward passage, and 45 minutes shorter on the eastward. But your biological clock goes on at the old rate, so the two clocks—the one inside you, and the one on your wrist—do not exactly synchronise.

However, biological clocks are more easily studied in lower animals, and I will describe an example which is very convenient for technical reasons, and is being analysed in several laboratories at the present time.

The common fruit-fly of our classrooms, and laboratories, *Drosophila*, begins life as a grub, then turns into a pupa, then becomes an adult. Normally the great majority of the flies emerge from the pupa stage at dawn. So if you have a culture bottle—that is a bottle with hundreds of developing pupae inside it—you find that the adult flies appear in daily bursts, always in the early morning.

Of course, that is very necessary, because the newly emerged fly has a soft cuticle through which water can rapidly evaporate. The cuticle hardens quite quickly, but if the fly emerged on a hot, dry afternoon, it might dry up before this could happen. Besides, its wings will not expand properly unless the air is fairly humid. So it comes out at dawn, which is, on the average, the coolest and wettest time of day.

Now, why do we suppose that emergence is controlled by a biological clock? Why cannot it be a simple reflex, produced by some physical change in the environment, like the light which comes at dawn?

In the first place, if the bottle of pupae is kept in constant darkness and at constant temperature, the flies still come out in bursts at intervals of about 24 hours. This proves that emergence cannot be a direct response to light or to a temperature change. There still remains the possibility that some other factor in the environment, something other than light or temperature but changing with the time of day, may be the stimulus which triggers off emergence. But that can be disproved by the following fact. The interval between bursts, in a culture kept in darkness and constant temperature, need not be exactly 24 hours. For example, in a culture kept under these conditions at 16° C., the interval between bursts is regularly 24 hours 30 minutes. This shows that the rhythm is not controlled by some external factor that varies with the rotation of the earth; if it were so controlled, the period would be exactly 24 hours; but it is not, so the clock must be something internal to the organism.

Under natural conditions, this rhythm is continually checked by the environmental changes in light and temperature. These changes stimulate the organism and serve to adjust, or reset, the clock. In the artificially constant conditions of the laboratory, the check is lacking so the emergence rhythm is not quite so exact. But the important thing is that the rhythm persists under these conditions, though now its period is not exactly 24 hours.

That is just one example of a biological clock, and all the evidence nowadays points to the conclusion that such clocks are practically ubiquitous in living organisms. They have been found in every major group, except the bacteria, and they control all sorts of activities. Living things, evolving on a spinning globe, have always been exposed to diurnally varying conditions; they have responded by adjusting their lives into rhythmic patterns that fit closely with the rhythmic pattern of the environment. If they had not done that, the environment would always be catching them by surprise.

But how have they done it? What are the essential parts of a biological clock, and what makes it tick? That question is still unanswered; but lots of people are trying to answer it, by studying clocks in different kinds of organisms, and finding out what happens to them when the conditions are changed.

One of the most curious features of these clocks is the fact that they are very insensitive to temperature. Most biological rhythms are accelerated twofold or threefold if the temperature rises by ten degrees. (The heart-beat of a frog goes faster if you warm the frog, and most cold-blooded animals consume oxygen faster as the temperature is raised.) Yet biological clocks—although they are affected by temperature—are affected very little indeed. This may mean that the fundamental mechanism of biological clocks is quite different from that of other biological rhythms. However, in the present state of our ignorance, it is even an open question whether all clocks, in all organisms, work in the same way; so perhaps it is hardly profitable to speculate about the relation between clocks and other rhythms in biology.

Another interesting point: the biological clock can be temporarily stopped, and started again, for example, by withholding oxygen. Going back to the *Drosophila* culture bottle, with the flies coming out in daily bursts, although it is kept under constant conditions: if you withhold oxygen for a period of, say, 10 hours, then re-admit oxygen to the culture bottle, you find that the *Drosophila* are still alive. Once again the flies emerge in daily bursts, but now the bursts come ten hours later in the day than they should. The clock must have been brought to a temporary standstill during the period of oxygen deprivation. Incidentally this observation makes it very hard to believe that any particular factor in the environmental cycle is acting as a signal for emergence.

The whole problem is a difficult one and of great theoretical interest. To find out how these clocks work, we shall have to throw more light on the whole nature of the living cell. And, of course, it is of practical importance too. If you fly by jet to America, you find at first that your own biological clock is five hours out of phase with the rhythm of your environment. It is the ocean liner story over again, but more so. You want to get

up in the morning, and go to bed at night hours before everybody else, and it takes a rather uncomfortable day or two to reset your clock.

If we knew more about how it works, we could perhaps hasten the process of resetting, and even do it in the plane on the way across, just as one can reset the watch on one's wrist. I think it would be difficult to exaggerate the usefulness of learning to manipulate the biological clock, especially in these days when planes fly faster and faster, and people dash about more and more. It may prove even more important tomorrow, if indeed it be true, as I suppose it must be, that space travel lies just around the corner.

For millions and millions of years, our stock has accustomed itself to life on a spinning globe. That is what our whole organisation is attuned to. What do you suppose will happen to us, when we get off it? There you have another question that has not yet been answered.

The Slow Life of the Sea

BY DR. D. M. ROSS

It is natural that we should think of animals as creatures which, in contrast to plants, move about actively on roughly the same time scale as ourselves. Yet some animals carry out movements that, by our standards, are incredibly fast. We find it difficult to move a finger more than five to ten times per second, but the muscles operating the wings of a house-fly contract and relax hundreds of times per second. We also find it difficult to move a finger very slowly; usually such a movement is jerky. There are movements, however, of some animals, that are so slow that they cannot be detected by the human eye. These movements are not so very different in time scale from the non-muscular reactions of plants, such as the opening of flowers and various bending movements towards the sun. It is mostly with these slow movements of some animals—notably sea-anemones—that I wish to deal here.

We tend to think about evolution as a process that has produced new structures and activities in organisms. In the animals in which these very slow movements are found, evolution seems to have gone into reverse. It has produced creatures which lack that feature which is most animal-like, the power of locomotion, creatures which have adopted a sessile existence that is superficially plant-like.

Amongst the invertebrates, there are great groups like the sponges, the hydroids, the corals, and that peculiar offshoot from the early ancestors of the vertebrates, the sea squirts, which settle on a spot early in their lives and remain rooted to it thereafter, as immobile as any plant as far as locomotion is concerned. They are not plants because they obtain their food by straining or capturing other organisms from the water; they cannot make their food from inorganic materials as plants do.

The early naturalists who first became aware of the animal nature of these sessile creatures called them zoophytes, and gave

many of them picturesque names recalling their plant-like features. Perhaps the sea-anemones, more than any other group of animals, possess features reminiscent of flowers in colouring and appearance. They also show features in the time scale of their activities that are going on at such a slow pace that I have chosen them to illustrate what I mean by 'the slow life of the sea'.

Sea-anemones are essentially living cylinders. If we imagine the base of the cylinder to be developed into an adhesive disk which sticks itself down on some surface on the sea bottom, say a stone, a shell or a submerged pier, and if we imagine the top of the cylinder to have a fringe of tentacles around the margin and a mouth in the middle, we have a mental picture of the essential anatomy of a sea-anemone. The lower adhesive surface is known as the pedal disk, or simply as the foot; the top with the mouth in the middle as the oral disk, and the upright wall of the cylinder as the column.

Looking at a sea-anemone in an aquarium or in a rock pool on the shore, one might say that it is completely motionless most of the time. Occasionally, the tentacles may be seen to withdraw suddenly and the whole animal to close up, in response to a sudden strong stimulus; one may also see great activity by the tentacles, followed by opening of the mouth, when food happens to be captured. Between such events, the animal seems quite inactive.

If we look more closely, however, it is possible to see that the animal's shape and appearance at one moment are not quite the same as they were a few minutes before. And if we test the matter properly by taking photographs every few seconds and then project these as a cine-film, speeding up the normal activity fifty to sixty times, we get a completely different impression. We then see that this apparently inactive animal is constantly changing its shape, becoming longer or shorter, bending to one side or the other, or passing wave-like peristaltic constrictions up the column, without pause. In fact, it now appears to be a very active animal indeed. What is more, these movements often have the appearance of being directed towards a definite goal, such as searching for food. So we learn that our impression of immobility was incorrect

and that these animals are, in fact, continuously active, but at such a slow time scale that we do not notice it.

Close observation and time-lapse cinematography also reveal that sea-anemones are not completely without locomotory powers. By puffing out the edge of the pedal disk and taking up a slightly forward position, and then sliding the rest of the pedal disk up to this position, a slow snail-like type of locomotion is carried on. It only moves the animal perhaps a couple of centimetres per hour but, again, it is exceedingly slow activity directed towards some goal. Some sea-anemones are able to carry out even more complicated, and apparently purposeful, slow activities.

Perhaps the best example of this is the way the so-called (and misnamed) 'parasitic anemone' deserts a surface on which it had settled in order to climb on to a shell occupied by a hermit crab. This process is a remarkable performance in which as many as ten distinct movements are carried out in sequence over a period of about twenty minutes, but going on so slowly that movement at any one time is hardly visible to the observer. Slow movements, therefore, are not just automatic repetitive rhythmical activities in these animals. Close study shows that they have features that appear to be purposeful just as the livelier behaviour patterns of higher animals are.

For several years now, I have been doing experiments on these slow activities of sea-anemones, to find out, if possible, what starts them off, and how they are controlled, in the living animal. These movements have a number of features that make them important for any general understanding of the way that nerves and muscles work.

Some of the muscles involved in these slow movements are found in the upright part of the animal, the column, and they are arranged circularly around the column so that when they contract the column becomes thinner.

If you take a sea-anemone and bathe it for several hours in a solution containing a great excess of magnesium salts, it becomes anaesthetised and it can then be dissected and isolated rings of the column can be cut out. These isolated rings of the column of an anemone can then be placed in a bath and attached to levers

to record their movements on a slowly revolving drum. When that is done, it can be seen that these rings are able to carry on movements which are apparently the same as those that occur in the intact animal. About once every fifteen minutes, such a preparation will give a contraction, an exceedingly slow one lasting two or three minutes, and then, having contracted, the ring will slowly extend again. These movements will go on for several days before the preparation finally gives up, usually by breaking through at some weaker place in the ring.

The work that such a ring preparation can do, considering that it is living on its reserves of food, is remarkable. I have calculated that an average preparation which survives for five days in a bath can do as much as 1,000 gram/centimetres of work during that time, that is, the equivalent of lifting a kilogram weight to a height of one centimetre. This is done by a preparation that weighs about two grams in which the weight of the muscle cannot be more than one-tenth of a gram. It is a prodigious performance. Clearly, the contractile processes involved in these slow contractions must develop energy and utilise it in a most efficient way. We do not know much about this at present.

The physiologist is also very interested in finding out what starts off movements of this kind. Do the contractions arise in the muscles themselves, or are they triggered off by nerve impulses delivered to the muscle cells from outside? This problem of distinguishing between 'spontaneous' and 'reflex' movements is constantly coming up in studies of rhythmic activities in animals.

It is not an easy matter to decide whether an activity is 'spontaneous' or whether nerves are required to start it off. Sea-anemones have nerves, difficult to see and trace, which run in a kind of network under the outer layers of the skin. We know that slow contractions which seem to be identical to those I have described in the rings can be caused by giving electrical shocks to a strip of the animal attached to the ring. Such shocks can only arouse the muscle in the ring by passing impulses through the nervous system, so it seems likely that in the animal the muscle contracts because it receives certain signals from nerves associated with it.

Besides moving very slowly, these muscles in the column of the

sea-anemone are also very slow to respond to stimuli, unlike our own muscles which respond almost instantaneously. By that I mean that if you apply electric shocks to them, there is a long delay before they begin to move. It is interesting that in any one preparation the delay is very constant, but there is a big difference between the top and the bottom of the column. In preparations taken from the top of the column, stimuli cause a response in about fifteen seconds, whereas preparations taken near the bottom respond after a delay of about two minutes. The reasons for this delay are obscure, but I believe these long latent periods, as they are called, can be very useful in trying to find out what happens between the moment when the shocks are given and the moment when the muscle begins to contract.

It is well known that nerves exert their effects on muscles through substances known as chemical transmitters which are produced at nerve endings when the nerve is active. The slow activities of sea-anemones are easily explained by the hypothesis that the nerve endings in the muscle slowly liberate a transmitter substance and that the muscle contracts when a certain amount of this substance has been produced. The difficulty in finding evidence for this idea is that, although I have tested many substances, very few of them have had any effects on these ring preparations.

The most effective substance I have found is adrenaline, the important hormone produced by the adrenal medulla in mammals, which, along with its near-relative noradrenaline, is the transmitter at the endings of the sympathetic nervous system. It causes contractions of the ring preparations that are very similar to those following electrical stimulation. The next step will be to see if adrenaline occurs in these animals and, if so, whether it occurs in larger amounts when the nerves are stimulated. Fortunately, there are good methods for carrying out such tests and the slowness of the activities should assist us in detecting such transmitter substances if they are present.

Vision in Deep-Sea Fish and Squid

BY DR. ERIC J. DENTON

As we go deeper and deeper into the ocean, daylight not only becomes dimmer and dimmer but also more blue in colour. This is because blue light penetrates oceanic water best. Daylight is made up of all the colours of the rainbow, and red light is absorbed from daylight in the first few yards of the sea. Then as we go deeper, orange, yellow and green disappear in turn until only blue remains.

People who go down in the sea in bathyspheres or bathyscapes tell us at that about 600 metres down they cannot distinguish daylight at all—even the blue light is now far too dim to see. They now see a multitude of tiny flashing lights for down there, where the light of day is so feeble, the animals carry their own 'living' light with them. With these lights they signal to one another, warn one another, they recognise one another and even trap one another. Some deep-sea fishes have lights inside their mouths so that, when the curious, unwary or deceived prey comes to look, he can be snapped up with the least possible effort. For some deep-sea animals there really is the danger of what amounts to walking 'down the lion's throat'. The sea is a very dangerous place in which to live and very few animals there can have the common human privilege of dying of old age.

For many delicate and fragile creatures the upper layers of the sea are far too well lit in the day-time for safety, so these animals prudently stay deep in the ocean where it is always dark. Yet, in the surface waters, which are so very dangerous, lies most of the ocean's food. Here, and only here, can the tiny plants, on which all life in the sea depends, receive enough sunshine to grow. We find therefore that at dusk great troupes of animals migrate to the surface layers to feed there in the comparative safety of the night. Such vertical migrations—up and down every day—may be about half a mile in extent.

What are the visual problems of animals with this kind of life?

In some ways they are much simpler than our own. Our eye is a miracle of versatility: it can see well in bright sunlight and can even give us useful information on dark moonless nights. Our eye can, in daylight, distinguish between the different parts of the spectrum. We see not only form but colour. The deep-sea fish never have to look at a bright light, and they have very little use for colour vision because virtually only one kind of light—that which looks blue to us—is available to them.

As we might expect the deep-sea animals have eyes which are highly specialised for the rather simple tasks which they perform—the tasks of seeing the broad field of dim daylight and the small dim flashing lights of other creatures. Such a high degree of specialisation means that in some ways their eyes are particularly simple, and therefore probably particularly simple to study.

Let us then examine the eyes of the deep-sea animals and compare them with our own. We shall do this by working from the outside of the eye inwards, looking at each structure we come to in turn.

As light goes from the air into our eye, the first surface it crosses is the curved cornea. Now, although there is a lens inside the human eye, the principal image-forming surface is the cornea. This can bend light because it has air on one side—the outside—and liquid on the inside. Clearly the fish cannot use this trick to form an image because its cornea has water on both sides. As we have all noticed, we ourselves cannot see clearly under water without a face mask, and this is because our cornea, once it has water on both sides, cannot help in image formation. In the fish all the task of forming an image falls therefore on the lens. In shape this is spherical like a glass marble but optically it is quite unlike a glass marble. It is beautifully contrived with properties varying continuously from the centre to the outside. The images which it forms are free from all those distortions of shape and colour which so trouble the makers of optical instruments. (The white opaque sphere which you will see if you look into the eye of your cooked fish is just the poor remnant of one of the best lenses in nature—one which far outstrips in performance any

made by man. If only we could preserve a fresh fish lens, what a magnificent microscope we would make!)

In our own eyes between the cornea and the lens comes the iris. This is the coloured part which gives our eyes their characteristic colour: blue, brown, green or grey. In our eye, the iris acts as a shutter. It gets smaller and cuts down the amount of light entering the eye when the light is bright. The deep-sea fish and squid never have to change the aperture of their eyes because the light reaching them is always so very dim. The iris in their eye usually just fits around the lens and so prevents stray light leaking past it. I say 'usually' because in some deep-sea fishes the iris is much bigger than the lens and it appears certain that light will pass round its sides. This does seem a very odd system—like a camera with a hole in the side—but we can be pretty sure there is some good reason for it.

Let us now go further into the eye, through the clear jelly-like media, until finally we come to that wonderful thin structure which lines the back and which is called the retina. The retina is the light-sensitive surface of the eye. Just as a film in the back of the camera contains coloured substances which react with, and are changed by, light, so the retina at the back of the eye contains coloured substances which are sensitive to light. Only light which is absorbed by these substances and changes them can be seen. Light which either does not reach the retina or which goes right through the retina is simply wasted as far as vision is concerned. Since these coloured substances decide which colours of light we can see and how well we can see them, you will easily understand why a study of their nature and properties has been one of the principal activities of people doing research on vision.

A few years ago it was generally thought that all fresh-water fishes had purple-coloured retinae whilst all marine fishes were thought to resemble man in having red retinae. Then we found a fish whose retina was an exception to this rule—the common conger eel. Its retina is neither purple nor red, but of a beautiful golden colour, the colour of a substance we christened chrysopsin or visual gold.

Conger eels are extraordinary fish. They begin their life in the

deep sea, come to our coasts, and then return to the deep sea to spawn when mature. We could then in some ways regard them as deep-sea fish. Now a pigment which looks golden to us will absorb blue light very well and therefore a golden pigment would be an ideal pigment for a deep-sea animal living where nearly all the light is blue in colour. We began therefore to wonder whether other deep-sea fish might not resemble the conger in this respect. Aboard our own research ship *Sarsia* and aboard the Royal Research ship *Discovery II* we studied some twenty species of fish: viper fish, lantern fish and hatchet fish, fish of all shapes and sizes. All had visual gold in their eyes. They not only had this eminently suitable pigment but they had it in enormous amounts.

At the best, only about one-tenth of the light energy entering the human eye is usefully absorbed by the red retinal pigments; nine-tenths of the light is wasted. In deep-sea fish over nine-tenths of the light entering the eye is absorbed by its golden pigment and only less than one-tenth is wasted. There seemed to be no exception to the rule that deep-sea fish had this special substance, visual gold, in their retinae; I say no exception, but there was one fish which one might consider to be a deep-sea fish which did not seem to fit in, the common fresh-water eel. This had been described by the great American authority, Professor Wald, as resembling a fresh-water fish in having a purple-coloured retina. This difficulty is now resolved.

The fresh-water eel has a life history the elucidation of which was one of the great surprises and triumphs of the study of natural history. The great Danish oceanographer, Schmidt, found that the eels hatch in the Sargasso Sea and then drift thousands of miles across the Atlantic as thin flat larvae which look quite unlike the eels we know. When they approach our coasts they turn into elvers and swim up our rivers and into our ponds. Here they live and grow for eight to ten years and here, in fresh water, they have the purple-coloured retina of fresh-water fish. Then finally they begin to prepare for their long journey back to the oceans—the yellowish eels become silvery and now, before they leave fresh water, their eyes change to become like those of the deep-sea fish.

The eye grows until its diameter is twice its original size, that is eight times its original weight, and as it does so the purple-coloured retina is replaced by a golden-coloured one and the eel is prepared for life in the deep sea.

Now another famous fish, the salmon, makes the reverse migration. It lives most of its life in the sea and then comes up river to spawn. But Atlantic salmon are practically never caught once they leave our coasts. At what depth do they live? Here the visual pigments furnish us with a clue for we are shown that the salmon parr, the salmon smolt caught on its way to an estuary and kept in sea water for several months, and the salmon returning, all have the characteristic purple-coloured retinae and never change to a deep-water form. It appears therefore likely that they live near the surface of the ocean and that we might profitably try to establish an oceanic salmon fishery industry.

Here I have described some rather simple answers which have been given to questions about the eyes of deep-sea animals. There are plenty of problems left to excite our curiosity. What, we may well ask, is the point of an eye as big as that of the giant squid—an eye sometimes 15 inches across and so bigger than a human's head? Why does another squid *Calliteuthis* always have one eye very, very much larger than the other? Why—and this is a very curious puzzle indeed—should some fish have luminescent lights which shine into their eyes? How can this possibly do anything but dazzle them? So we can easily pose obvious but as yet unanswered questions.

Not only in their vision, but in every way there is a lot more we would like to know about the deep-sea animals. For although most of us are accustomed to regard these animals as rare and bizarre, they are everywhere in the oceans, and since the oceans cover most of the globe, a moment's reflection will convince us that we, and not they, are the curiosities of nature. They are the common everyday creatures of the world.

Bees, Moths and Memory

BY DR. A. D. BLEST

We humans take the act of communication by speech very much for granted. Yet no other feature of our behaviour distinguishes us so surely from all other vertebrate animals. The only other creature with powers of communication apparently comparable in variety and precision to our own is an insect, the honey-bee. The elegant and now classical experiments of Professor Karl von Frisch have shown that when the foraging bee returns to her hive, she gives to her fellows information about the quality, direction and distance from the hive of the food source which she has just exploited. She does so by performing a special dance on the surface of the honeycomb. In this dance are encoded all these items of information.

It is true that the language used, unlike ours, is not very flexible; the incidentals of the journey, whether perilous or peaceful, cannot be imparted by it. However, for an animal so far removed from us on the evolutionary scale, the achievement is an astounding one, and we need no excuse for investigating it.

I shall talk about just one piece of information which the dance contains—the distance of the food source from the hive. Further, the experiments which I will describe may help us to understand only one aspect of this act of communication, the method by which the foraging bee remembers or registers the distance through which she has flown, and then converts this information into a component of the dance. In my own experiments I have used not the honey-bee, whose complicated behaviour makes it difficult to handle in the laboratory, but a Brazilian moth, *Automeris aurantiaca*; and I have used *Automeris* because part of its natural behaviour may be treated as a very simple model or analogue of the dancing behaviour of the bee.

To begin with, let me describe what the returning bee does after she has re-entered the hive. First, she disgorges her load of honey, which is received by her hive-mates, and then she starts

to dance on the surface of the comb. If, say, the food source was more than about 45 metres from the hive, she runs in each unit of the dance over a complex path rather like a figure-of-eight. In the course of each unit she performs a straight run, and throughout each straight run the abdomen is wagged rapidly from side to side. The sequence of movements is repeated many times by each returning bee, which soon recruits a train of followers who keep their antennae in contact with the dancing bee's abdomen. These recruited bees correctly interpret the dance, and fly out to the feeding ground, having first, as Dr. Lindauer has shown, taken on sufficient honey as fuel for the journey, neither more nor less than will be required. What components of the dance give them their clues?

Soon after the dance was first discovered, it was seen that the further the food source is from the hive, the more slowly is the dance performed, and the longer is each straight run. This relationship between the rate of performance of the dance and distance is not the simplest possible, and would not seem to be well-suited to the needs of communication.

Professor J. B. S. Haldane and his wife, Dr. Helen Spurway, suggested that perhaps the number of wagging movements in each straight run of the dance might give a simpler measure of the distance flown. Such has turned out to be the case, although the demonstration in itself cannot prove that this is the form of the message to which the recruits actually respond. Nevertheless the number of waggles in each straight run of the dance increases not quite linearly with the distance flown; this means that the message is a relatively simple one to interpret, and allows a strong presumption that the message is contained in the wagging phase of the dance.

The problem, then, is this: how does the honey-bee 'know' how far she has flown? There are several potential methods available to her. For instance, as she flies wind passes over her head and antennae; both are equipped with structures—sense-organs—which are sensitive to air currents. So perhaps the length of time they were stimulated might be recorded by the brain. Then there are other sense organs so situated that they can record

the number of wing-beats during flight, and this information again might be used to record the duration of flight activity.

During her flight, the bee uses up her supplies of energy-giving substances such as sugars, removing them from her blood, and replacing the depleted blood-sugars from the contents of her gut. So changes in the sugar-levels of either blood or gut-contents might provide information about flight performance. There are other possibilities, but these—air elements, wing-beats, sugar-levels—are the most important. How does the moth, *Automeris*, help us to assess them?

When an *Automeris* is resting, it remains in a special posture, with its wings folded over its back into a sort of tent. Each time it assumes this position from any preceding activity it performs an act which Dr. Margaret Bastock and I first described as 'rocking'. The moth 'rocks' from side to side, like a cradle. The movement is cleanly and neatly performed, and it is an easy matter to count the number of rocks enacted in a single completed settling movement.

Here, then, is a rhythmic movement which can be made to follow flight, and which is easy to measure quantitatively. This is a closely parallel situation to that of the rhythmic part of the bee-dance, with one unfortunate difference. We do not know what rocking is used for, but it is certainly not used for communicating anything whatsoever. Six months of field work which I undertook in 1958 in the Central American jungle where species of *Automeris* are abundant served only to disqualify all the hypotheses which I had carefully prepared to explain its function.

Experiments on the rocking response can be performed with some precision. I keep *Automeris* in a constant temperature room at 20° C., and only use moths whose age I know. In ideal conditions they live for about a week. Instead of allowing the moths to fly freely, I remove their wings and suspend them in mid-air by a clip attached either to their bodies or to the thorax. Moths deprived of their foot-hold in this way can be made to fly for long periods. As soon as they are unclipped and replaced on firm ground, they rock. When an individual moth is repeatedly flown and tested, the number of rocks is found steadily to increase,

and the relation between flight duration and the number of oscillations is approximately linear. In other words, however long the moth has already flown, a given further period of flight always adds the same corresponding number of rocks to the response when it lands (say two rocks for every three minutes it has flown). Thus, if we know the age of an individual moth, and the number of hours or minutes it has already flown in its life, we can predict, almost exactly, the number of rocks which it can be expected to give when it settles.

This system allows experiments which test all the possible pathways by which flight performance might be registered in the nervous system, and I shall not describe all these experiments in detail. When the antennae and wind-receptors of the moths are removed, for example, the mutilated individuals still accumulate oscillations in the normal way as they 'fly', so we know that the perception of wind-currents does not play an important part in the registration of flight performance.

Similarly, the muscles which sustain flight may be readily cut in such a way that the flight response is performed with its most essential part, the movement of the wings, missing entirely. Yet, such moths accumulate rocks at the normal rate while suspended in the flight position. Clearly, they cannot be recording their own wing-movements. The entire blood of a moth which has just flown can be replaced with an artificial solution whose sugar concentration is determined by the experimenter; yet this drastic procedure does not affect the strength or the stability of the rocking response. We know, therefore, that the moths are not registering those changes in their blood composition which are induced by flight. Finally, adult *Automeris* do not feed; indeed, their mouth-parts are vestigial, and they are probably unable to take any food at all. Their nourishment is all obtained in the larval stage and stored in their blood. *Automeris* are presumably never hungry; at any rate, flight does not affect the contents of their permanently empty gut.

The conclusion from these tests is simply this: what the moths record is merely the length of time during which their central nervous system was active in sustaining flight behaviour. If a deaf

and blindfold man were to run for an hour, and then tell us just how far he had travelled, or even how long he had been running, we would be, very properly, surprised. Yet this is really what both the moth and the bee succeed in doing.

I have entitled this chapter 'Bees, Moths and Memory'. Both the bee and the moth in a sense 'remember' the details of their flight performance. I need not emphasise how different, in fact, this achievement is from our own memory. It is, for example, quite inflexible; the insects' nervous systems allow for the storage of only one item of information, and the store can only influence one or two other parts of their repertoire of behaviour patterns. This influence is obligatory; neither the memory, nor its consequences for behaviour, can be switched off.

This very limitation, however, makes the problems posed by the rocking response and the bee-dance peculiarly attractive to the experimental zoologist concerned with learning processes. In most animals, the establishment of a memory necessitates the sorting of a wealth of perceptual information; the changes in behaviour which reveal that a memory has been established are somewhat plastic, and are far from being exactly predictable. When we start to analyse the effect of experimental procedures upon memory, we need to know where the sorting processes end, and memory begins, and, all too often, the distinction is difficult to make. *Automeris* presents no such difficulty; the information entering the nervous system is of just one kind, and the activities which it generates are equally stereotyped.

This represents, then, one of the simplest of all memory systems. I believe that there is a quite real hope that we may be able to discover how it works. If we succeed, the solution may suggest some of the answers which the infinitely more complex memory systems of higher animals and of ourselves still require.

Mind, Matter and Machines

BY DR. GREY WALTER

Your picture of the world is a 3D miniature, contained in a small frame of finely wrought bone. This is your brain, a pinkish-grey jelly containing more than 10,000 million nerve cells, all capable of signalling to one another inside your skull. Think of the colossal scale of this signalling—like five planets as densely populated as our earth, with a telephone or radio link between all and every person—what a problem for the engineers that would be! This microcosm of imagination and reflection, mirroring in dynamic detail your inner private view of the outer macrocosm has in effect solved the still indefinable complexities of communication by evolving.

A few thousand million years ago there were no brains in our corner of the universe—not even the elements of a brain. Now there are thousands of millions. They come in several sizes from the minute ganglia or nerve knots of an octopus to our own headfull of nerve soup and the even bigger mass of convoluted grey matter of the charming dolphin. In the remote Genesis of life there was indeed Light—there was energy, and there were the chemical elements and simple compounds that constitute our flesh. By the interaction between light-energy and these elemental substances there arose, by means we are only beginning to guess at, the self-sustaining organic molecules that were the tenuous but pertinacious ancestors of us all—and of all our pictures of all possible worlds.

Unless we are very cold or hungry, we tend to forget that the light-energy that spawned us in the primordial soup is still essential to our existence. Our bodies regulate themselves, and our societies so protect our bodies, that when we consider our brains we think first of thinking—of the mind. But a brain is greedy, as well as pensive. In fact, thinking or vacant, waking or sleeping, a human brain uses about one-third of all the energy of the body it governs. In electrical terms it consumes about 25 watts of

power, and it gets this from the slow burning of about one teaspoonful of sugar every hour. This energy is used up in the extremely involved and delicately balanced chemical reactions within the brain cells; these keep the cell batteries charged, so to say, and in every transaction between brain cells there is an incessant electrochemical discharge and recharge process.

The electric component is of special practical importance not only because it forms an essential part of the signalling process in the brain, but also because, fortunately for us who experiment on the brain, some of the electric signals can be picked up from the surface of the scalp. These stray brain signals are very small indeed, only a few millionths of a volt, but with modern techniques they can be amplified and analysed in enough detail to help the diagnosis of some types of brain disease and mental disturbance. This is of great value in the clinic, but we cannot yet claim to have broken the code the brain uses, but we know enough about it to be able to guess whether the messages passing from one part of the brain to another are routine, or news flashes or distress signals.

This is really very tantalising, like hearing a foreign language in which one can recognise something of the mood but nothing of the matter. There are plenty of surprises too—the most disturbing one was when Hans Berger in Germany discovered about thirty-five years ago that the more functionally active a brain is, the less regular and prominent are the electric signals that can be picked up on the scalp.

This is particularly true of what Berger called the 'alpha rhythm', regular electric oscillations at about ten waves per second, that are largest and most rhythmic at the back of the head when the eyes are shut and the mind is blank. In most people opening the eyes or thinking hard, particularly in visual images, stops the alpha rhythm. But in some people the waves persist even with the eyes open and in others again there never seem to be any alpha waves at all, even with the eyes shut. These differences suggested to us some years ago that alpha responsiveness might reflect something in the nature of a mental language or accent, as it were. We must suppose that all human brains work on the

same basic principles, but there is enormous scope for variation in the way in which these principles are applied, just as the mechanism of human voice production permits the development of hundreds of different languages.

We are not sure how deep these differences in brain personality go, or how they are related to mental personalities, but we suspect that some of the important differences between brains are based on slight inborn traits which are constantly and cumulatively amplified by culture and experience, as a child born slightly right-handed will become more and more literally dexterous, and completely right-handed.

The odd discrepancy between regularity of electrical rhythm and functional activity in the brain, whatever its relation to human character, is still lacking a full explanation. One possibility is that the electric rhythms represent a process of signal sorting and searching in the vast labyrinth of cerebral archives—the memory. We must remember that the amount of information reaching the brain from the senses is really overwhelming—you cannot attend to everything all the time—and the incoming messages are meaningless unless they are related to one another and to previous messages stored in some memory register. The selection of significant associations must be very orderly and systematic or we should be even crazier than we are, and the regular ten-per-second sweep of the alpha rhythms over the brain looks rather like the monotonous scanning of a great dictionary page by page and line by line for some particular word or meaning.

We can see why the rhythms stop or break into sub-rhythms when the attention is engaged—this is just what you do when you find a word you are looking for in a dictionary: you stop looking for it. If this is the sort of mechanism that goes on in the brain then I suppose people with no alpha rhythms are always finding something of interest and are never just turning the pages idly. This makes sense for me because I have no alpha rhythms myself and I am certainly quite feverishly fascinated by all the exciting things going on around me, while my colleagues with abundant alpha rhythms look at things more soberly and are quite suspicious of my width of enthusiasm—and I am sometimes a little impatient

at their sobriety. Knowing these differences helps us to get along, though.

As well in the alpha rhythms, there are many other sorts of brain rhythms associated not so much with vision and imagination as with feelings and frustration; there are also very slow rhythms found in sleep and in young children. Study of these rhythms is helping us to understand how people grow up and grow old.

Most of the basic truths about brain mechanisms still just elude us, but I think we shall have a pretty firm grasp of them before the end of the century. Even before then, partly because of our growing understanding of living brains and partly because of the vast progress in electronic techniques since the second world war, we shall be seeing spectacular advances in the imitation and amplification of brain function. There are already several species of artificial animal that mimic the behaviour of very simple living creatures. I built the first one myself about fifteen years ago, and there are already many progeny in various countries. (They are used for teaching and experiment.) And, of course, there are electronic computers that solve intricate numerical and logical problems with great speed and accuracy.

The rate of progress in the mechanisation of intelligence has not been quite as fast as was expected because human brain labour is still pretty cheap and versatile. Machines with anything approaching human intelligence—in the sense including initiative, creativity, discrimination, learning and inspired guesswork as well as formal problem-solving—would be very expensive indeed.

The nearest we have come to intelligent machines are those designed for automatic translation, but these are making heavy going just now. One American machine for translating Russian kept introducing allusions to a 'water-goat' into engineering texts. No-one could think how such an improbable animal as a water-goat could fit into the rest of the machinery until the original text was scrutinised. The reference was to a 'hydraulic ram'. This is no worse than many human translations, and the rate of conversion and speed of translation is already very high, but we must beware of water-goats in this unexplored frontier between the domains of flesh and metal. The exciting part of this

development is that brain-like machines are already helping us to study real living brains and to analyse the complex electric rhythms I was referring to earlier—a task that no human being could perform unaided.

No sketch of the contemporary world of brain research would be complete without a hue of mystery because this is what catches the mind's eye. For me there are two great obscurities in our picture: memory and sleep. We cannot yet conceive how the brain can store the enormous amount of information it must have to govern our mental lives and at the same time receive impressions, control movements and all the rest. Nor do we understand how or why we sleep or need to sleep; neither of these phenomena has a precise satisfactory mechanical analogue though both are reasonably accessible to experiment and study. Perhaps, as the psycho-analysts imply, the solution may be found in the interaction between these mysteries, the dreams that console the frustrated, terrify the anxious and seem to warn the superstitious sleeper.

Certainly our picture of the dark, private world within our heads is not a static one. It is a world of change, where even in apparent torpor of sleep, fantasy, invention and exploration mirror and generate the extension and adventure of human action.

How Much Sleep Do We Need?

BY DR. R. T. WILKINSON

Animals, small babies and the occasional adult often give the impression of waking up only when they have to; most adult humans, however, seem to be moving towards a policy of sleeping as little as possible. Clearly for each one of us there must be an optimal amount of sleep; less will impair our powers of survival and advancement, more will reduce unnecessarily the time we have to do these things. The question of how much this is becomes increasingly important with the growing potential of our civilisation for good or evil. Yet, despite the importance of this question, it is probably true to say that up to 30 years ago not only could we not answer it, we could see no research tools which might eventually enable us to do so. Since then, however, there have been important developments which have changed the picture; in particular new forms and techniques of neurophysiological measurement have emerged and, secondly, experimental psychology has developed better methods of evaluating human performance and behaviour. Studies, for example, of body and eye movements, of sensory thresholds and above all of the electrical potentials of the brain during sleep encourage us to think that we may be able to assess with useful accuracy the depth or quality of sleep.

In carefully controlled experiments also the amount of sleep has been varied to find the effects of lack of sleep upon performance and upon physiological changes in the body, especially those which accompany the effort to maintain normal behaviour and working standards in spite of sleep deprivation.

These and other advances are still at an early stage of development but the fact that studies of this nature multiply yearly suggests that before long we shall have at our disposal the means to a new and more scientific approach to the question of how much sleep we need.

As we pause on the frontier of this advance, however, it may be salutary to assess the state of our present knowledge of this question, if only to appreciate fully how very little we really know about it at present, and the importance of learning more.

There must be few questions on which responsible opinion is so utterly divided. There are some who think we can leave the body to regulate these matters for itself. 'The answer is easy,' says one authority. 'With the right amount of sleep you should wake up fresh and alert five minutes before the alarm rings.' If he is right many people must be undersleeping, including myself. However, we must remember that some people have a greater inertia than others. This is not meant rudely; they switch on slowly, but also they are reluctant to switch off; they are alert at bedtime and sleepy when it is time to get up, and this may have nothing to do with how fatigued their bodies are, or how much sleep they must take to dissipate it.

Indeed, this may beg a question. From animals we get the impression that it is satiation rather than fatigue which promotes sleep; many of them appear to wake mainly to satisfy their bodily needs; during the rest of the time they return to the negative state of sleep. This may be true for adult humans also, but with the important difference that their needs are often so complex and long-term in nature that they can never be completely satisfied. That may mean that other factors, habit, choice and fatigue must enter to play the major part in deciding how much sleep shall be taken.

Habits can change, however, and choice can be influenced by external pressures in ways which may lead to periods of sleep bearing little relation to the state of fatigue of the body and the real need for rest.

Other people feel sure that the current trend is towards too little sleep. To quote one medical opinion: 'Thousands of people drift through life suffering from the effects of too little sleep; the reason is not that they can't sleep but that they just don't.' One can sympathise with this impression; like advancing colonists, we do seem to be grasping ever more of the land of sleep for our waking needs, pushing the boundary back and reaching,

apparently, for a point in our evolution where we will sleep no more. This in itself, of course, need not be a bad thing; what could be disastrous, however, and what these people fear, is that we should press too quickly towards this goal, sacrificing sleep only to gain more time in which to jeopardise our civilisation by actions and decisions made weak by fatigue and neurosis.

To complete the picture there are those who believe that most people are persuaded to sleep too much. Dr. H. Roberts, writing in *Everyman in Health*, asserts: 'It may safely be affirmed that, just as the majority eat too much, so the majority sleep too much.' One can see the point of this also; it would be a pity to retard our development by holding back those people who are gifted enough to work and play well with less than the average amount of sleep, if indeed it does them no harm. If one of the trends of evolution is that more of the life span is to be spent in gainful waking activity, then surely these people are in the van of this advance; if they can be efficiently active for longer than their fellows then, in a truly Darwinian sense, they and their children will be more likely to survive. We should not persuade them to sleep more than they do unless we are sure that they need to.

And, of course, we are not sure. Not only are we unable to give a formula for individual sleep requirement, we cannot even give confident averages for the different age groups. This is because we have no substantial scientific evidence to draw from and opinions based on clinical evidence present a picture which is too contradictory to be a dependable guide.

We have already seen how general statements can differ; a few examples will suffice to show that this applies also to quantitative assessments of the amount of sleep we need. If I go to my local public library for information, this is what I find: *Stedman's Medical Dictionary* gives an average of 8 hours for men and 9 for women. From the *Family Doctor* come these statements: 'Men and women rank equally in sleep need. Most of us are content with 7 hours or less.' And elsewhere: 'Most folk need between 7 and 8 hours.' The *Good Housekeeping Encyclopaedia of Family Health* advises the conventional round figure of 8 hours.

Confidence in the value of clinical assessment is further shaken

when we turn to the one field which is well documented scientifically—the sleep needed by the very young. Babies in the first few weeks of life appear to wake only to satisfy their basic needs of food, warmth and evacuation; here it may be reasonable to take the observed amount of sleep as a true index of the sleep required. For many years an official American publication on infant care advised that the week-old child should sleep for 20 to 22 hours out of the 24; by 6 months this should reduce to around 16 hours. Now three studies have been made of the actual hours slept by children in the first 6 months of life and all return a figure less than this; the last, a particularly thorough examination in 1953, showed that a group of infants in their third week averaged only about 15 hours' sleep a day and that by 6 months this figure had fallen to around 14.

In spite of this research the earlier idea still persisted; in 1956 the *Good Housekeeping Encyclopaedia of Family Health* assured its readers that 'a baby sleeps for about 22 in every 24 hours', and *Black's Medical Dictionary* (1958) still gives a figure of 20 hours for the first year of life. Clearly we have some cause to doubt these statements made, presumably, on the basis of clinical experience; would similar assessments of adult sleep requirements fare any better if we had scientific evidence to check them against?

Let us see what evidence there is, first, on how much sleep we actually take. This appears to rise with age up to 20 in this way: 13 hours at 2 years, 11½ at 5, just under 10 hours at 10 years and about 8½ hours between the ages of 15 and 20. These, of course, are averages and individuals may exceed or fall below them by as much as 2 hours. Beyond 20 years we know little; in one experiment it was possible to compare people in their twenties with others between 48 and 55. Surprisingly the older group slept more, admitting an average of 8 hours compared with 7·4 hours for the younger people. This may of course have been the result of upbringing and habit formation. It does not bear out the idea that we sleep less as we grow older, but perhaps this does not happen until after retiring age; again we have no comprehensive figures.

We have noted before, however, that the sleep actually taken by adults may not represent their real needs. What do we know of these? If a general sense of well-being is any guide to adequate sleep a relevant experiment is one in America where college students were asked to rate 'how good they felt' and then say how much sleep they had the night before.

The happiest group were not the average people taking about 7·3 hours sleep but those with over 8 hours, followed by those with more than 9; those sleeping less than 6 hours were the most miserable. This suggests that most people undersleep; but, of course, it may just be that unhappy people are the type to sleep less; there need be no causal relation.

Another direct approach is to get people to vary their sleep and observe the result. There have been small-scale attempts to do this. One investigator reduced her sleep by half for three nights and found she worked better! Two others curtailed their sleep regularly to find that although they worked as well this may have cost them more in terms of energy expenditure. Yet another could find no effect on one subject of going for a week with sleep reduced by half.

A novel approach has been to examine the sleep of men in the Arctic where for half the year there is either continuous daylight or continuous darkness. Thus removed from the pressures of normal life and the discipline of the 24-hour cycle of day and night these men, when allowed to sleep freely, still averaged, again with wide individual variation, just under 8 hours' sleep a day. But now the sleep was taken in a series of distributed spells, rather like that of animals such as the cat or rabbit whose senses make them independent of light and darkness. This may suggest that we also might benefit from breaking up our daily sleep, for has not artificial light made us less dependent on the same diurnal cycle of light and darkness? Perhaps, to start, we might take an afternoon nap at the expense of a shorter period at night.

Indirect evidence on the amount of sleep we need comes from studies of what happens when we do without it. At first sight these suggest that we do not need as much as we take. It has been difficult to show any effect on performance of as little as one night's

loss of sleep and even after three days awake we can expect normal efficiency in a man taking responsible decisions in a job which he finds really absorbing and exciting. Furthermore, when at last he is allowed to sleep he will probably wake after some 12 hours and show only a small after-effect.

These laboratory observations are borne out by examples in everyday life. The recent spate of marathon walks, chess contests, darts matches and dancing tournaments show how people can maintain physical effort with very little sleep over periods of more than a week. It seems clear that the human body is equipped to override the need for sleep in order to meet emergencies of quite long duration with faculties unimpaired. However, this reversibility of the effect of loss of sleep in face of urgent and absorbing demands may be the greatest source of danger.

People may think they are more efficient than they really are. I remember talking to a man who was playing a vital and interesting part in a rather difficult and prolonged exercise: his opportunities for sleep over five days were few and he said: 'When I find myself making a silly mistake I know it is time to knock off for a little sleep.' But, of course, this is too late. We cannot afford to have key men await the warning of mistakes before they take rest; too much depends on their decisions these days.

Again, there is some suggestion that maintaining normal performance in spite of insufficient sleep may cost the body more in terms of effort. Could such a drain of resources accumulate over perhaps months of undersleeping and culminate in a sudden breakdown with irrevocable errors in judgment? These are questions to which research to date has given no answer; understandably, for we cannot expect answers to come easily without considerable research effort. The effect of partial or complete loss of sleep, for example, cannot be assessed by a half-hour test on one man. A sufficiently large sample of subjects must be doing what approaches closely to a normal day's work.

As with heat studies we need to 'acclimatise' the subject to the experimental situation, to the lack of sleep itself, and to the tests themselves if they differ from normal work. In other words the experiment should be spread over periods of months, not days.

No experimental studies so far have met all those requirements, probably because they demand more resources than space-conscious communities will provide for a problem as mundane as the optimum ratio of rest and activity in humans.

On Making Up Your Mind

BY D. E. BROADBENT

In many cases, the modern world requires men and machines to work together as a team. The machine provides physical strength, speed, or the ability to perform vast numbers of routine operations without error. The man brings to the partnership his adaptability and his power to decide between different courses of action.

One example of a system of this kind is the modern machine for sorting letters in the Post Office. A man is needed to read the address on the envelope of a letter, and to press a series of buttons indicating which way the letter should go. The rest of the process can be fully automatic; purely mechanical devices will take the letter away and put it with other letters going to the same place.

The speed with which the man makes his decision about each letter, however, decides the speed with which the whole system can operate. When work is so arranged as to reduce the physical effort and time needed to execute decisions, a fresh importance is given to the time taken by the man in his choice of the correct action. For this reason there has recently been a greatly increased interest in the 'reaction time' which elapses between the occurrence of some event and the response of a man to that event.

The first and most obvious fact about reaction time is that it gets shorter when the probability of having to make that particular reaction gets greater. The more likely an event is, the quicker one responds to it.

Suppose I get a man to look at a screen on which numbers can be flashed, and provide him with a set of push-buttons so that he can indicate which number has appeared. If there are only two possible numbers and two buttons, he will take perhaps a quarter of a second to make up his mind which key to press. If there are eight possible numbers and eight buttons, he will probably take over a half second—more than twice as long. This means that the machinery in our brains, which connects the sight of the number to the pressing of the button, cannot consist simply of a

set of quite independent links, one for each combination of sight and action. A machine like that would take just as long to respond to a signal, no matter how few alternative signals might have had to be considered.

What sort of processes can we imagine that would take longer when there were more choices? One might suppose that the brain considers each possibility in turn, one at a time until it reaches the right one. This would obviously take longer when there are more possibilities, but we do know that it cannot as a general rule be the way that these decisions are taken.

The reason is that a process of this sort will take a time which is proportional to the number of possible actions; adding one extra choice will increase the time by the same amount no matter how many choices there are already. So, if this view were true, the reaction time when there are four possibilities ought to be half way between the times for two and for six possibilities.

This is not what is usually found; it is much more common to find that the time for the four-choice situation is half way between the times for two and for eight possibilities. That is, the time increases by the same amount whenever the number of choices is doubled. This relationship has sometimes been called Hick's Law, after Dr. W. E. Hick of Cambridge. It means of course that one extra push-button makes very little difference if there are already a large number to be considered.

This kind of law is a familiar one in some fields of engineering, as well as in the study of human behaviour. The maximum speed at which messages can be sent over a mechanical communication system—a radio or teleprinter channel, for instance—is related in just this way to the probability of the messages. The reason is, crudely, that if a message is very common and happens frequently, one can arrange some very brief code signal which will be quite adequate to convey the message. However, if a message is one which only occurs very rarely, a more cumbrous and lengthy code is required.

On the average the best possible arrangement of the code will be one in which the time taken for a message increases equally every time the probability of that message is divided by an equal

amount. So one is led to wonder whether the brain acts like one of these man-made systems: whether it forms a single channel or pipeline for conveying information from the eyes, the ears, and other senses to the muscles. If so, is there something in our heads that carefully adjusts the code, which the brain uses, so as to secure maximum efficiency in the particular situation?

A certain amount of evidence to support the pipeline theory of the brain comes from experiments in which two signals are delivered to a man, one just after the other, and he is asked to react to both. In such cases he often makes a very slow response to the second signal, as if the pipeline was blocked by the first signal and the second one had to wait for a clear passage.

People playing games frequently make use of this kind of effect, by doing something which makes their opponent start some counter-action—whereupon they make a quite different move before the opponent can recover. Experiments on this point form a whole topic in themselves, because there is some evidence that the eyes and ears only take in information from the pipeline intermittently rather than continuously; and there is also a possibility that with very considerable practice a man may be able to split himself into two separate channels, each working rather slowly. But the general trend of the results is in favour of the view that the brain acts as a single channel.

In recent years, however, some awkward results have begun to appear from experiments. If a man has to push buttons in response to numbers, the link between stimulus and response is rather indirect and unnatural. It is very understandable that the reaction time can be reduced by using stimuli and responses which have a more obvious connection with each other: for instance, putting a small lamp beside each button, and making the lighting of the lamp the signal for pressing the button. But this not only speeds up reaction time; it also reduces the amount of extra time needed for improbable signals.

In extreme cases, with well-practised men using extremely natural actions such as pressing down with a finger that has been touched, there may be no difference at all between the time to react to one of two possibilities and the time to react to one of

eight. When this sort of result appears, it is quite clear that the brain is not acting as a single channel which adjusts its code to match the probabilities of the messages going through it.

Various theories have been put forward for these rather uncommon and abnormal experimental results. There is the possibility that in these cases the links connecting the sight of a certain light and the action of pressing a certain button do become completely fixed and independent of each other: like the quite separate wires which link subscribers on a hand-operated telephone exchange.

On this view highly learned associations become automatic and almost reflex, while less well-learned actions are decided upon by a more conscious process which is indeed single-channel and limited in its rate of deciding between alternative courses. There are other theories, too, but the one which I personally prefer is due to Stone of Cambridge.

According to this idea, each possible signal arriving at the eye or ear does have a quite separate link within the brain to the corresponding action. When one of the signals arrives, the appropriate link becomes active. However, there is a certain amount of random activity going on in all the links all the time, and so if one were to look at them very briefly, it might happen that the most active link was not the correct one. The longer one went on looking, the more likely it would be that the link with the greatest total activity was the right one. A quick glance at a landscape does not distinguish between trees shaking in the wind and the more sustained motion of a car: a longer look does so more certainly.

So one can think of the brain as setting a certain critical time after which it will make the response according to the link which has been most active; and the setting of the critical time will for a certain percentage of errors have to be longer if there are more alternatives, because that will give greater scope for chance factors. The more trees there are, the longer one must look to be sure that one saw a car. The process which fixes the time must consider the whole situation, not just part of it, and so the time for one reaction does depend on all the others.

The mathematics of this view are complicated, particularly as there are several possible variations on it, but it seems clear that it does explain Hick's Law. It does say, when you work out the implications, that reaction time will increase roughly equally whenever we double the number of alternative actions. But of course the amount of the increase will depend upon the amount of random irrelevant activity in the appropriate parts of the brain, and one can well imagine that this is less in practised and natural tasks. So this theory explains all the present results with a single mechanism. In addition, it predicts that in certain cases Hick's Law will only be approximately true; and further experiments ought to be able to test this possibility.

The present atmosphere in this field is therefore one of busy investigation rather than settled conclusion. However, there are enough findings already to be of some use to the designers of machines, and there are also certain broad conclusions about the workings of the brain. We do know that even such simple decisions as the sorting of a letter are not to be explained solely by the independent associations or nervous connections which earlier psychologists and physiologists conceived. The brain is more complex than that. But by measurements of this sort we hope to uncover its secrets.

How the Eyes Deceive

BY RICHARD L. GREGORY

If we walk up to an object the images in our eyes will grow like a balloon being filled. They double in size whenever the distance is halved—but we do not see anything like this. An object normally appears of almost the same size over a great range of distances. You can test out your own perceptual size constancy mechanism, as it is called perhaps rather pompously, quite easily here and now. Take two equal-sized objects—say two coins—and hold one at arm's length and the other at half that distance. The images on the retinae of your eyes will be quite different sizes for each of the coins. If the nearer coin is at half the distance of the further, its image will be just twice the size. Now look carefully at the coins. Does the nearer one *look* twice the size of the further one? The answer is—it does not; it will look almost exactly the *same* size, although the images in the eyes are quite different.

We also find perceptual constancy for shape. If you look at one of the coins obliquely, it will look like an ellipse, but it can be shown that it does not appear as elliptical as the image in the eye. The perception is more like a typical view of the coin from almost above it.

This constancy mechanism involves changes in the effective size and shape of retinal images: it is a subtle scaling mechanism in the brain.

Now there are many simple two-dimensional shapes which produce illusions. This is a very curious fact, and one which has bothered writers on perception for at least a century. Many kinds of illusions may occur: increase or decrease in the length of lines; bending of straight lines; tilting of lines away from the vertical, and so on.

These illusions are extremely widespread—they are found to some degree in primitive people, and have been found also in birds and even in fish. They are also found in the most sophisticated humans. If you draw the following simple figures I think

you will see what I mean. First draw a pair of lines nearly vertical, but closer together at the top. Then add to these two horizontal lines between them but not touching. If the horizontal lines are drawn of exactly equal length, they will not look equal. The upper line will look considerably longer than the lower one. Your drawing should look like railway lines going off to the horizon, and your horizontal lines will look like sleepers, though not touching the 'rails'. The upper horizontal 'sleeper' would be further away than the lower if this was really a scene in a normal three-dimensional space, and this may provide the key to the problem of why illusions of this sort occur.

A second and even more famous illusion is simply two arrows. Draw two parallel lines exactly the same length, and side by side; then add arrow heads like this: on the first line draw ordinary arrow heads on both ends—simply a couple of V's facing each other. On the second, add V-shaped heads but the other way round, so that they face outwards away from each other. You should now have a pair of arrow figures, one with arrow heads pointing inwards and the other pair outwards. Now the shafts of the arrows will look different lengths, although they are actually the same length. The inward and outward pointing V's have changed the apparent length of the lines joining them.

Why should the non-parallel lines in the first figure—and the inward and outward pointing arrows in the second—produce distortions in perceptual space? Many answers have been suggested: that fields of force in the brain are produced or upset; that the normal eye movements are upset and many other theories, but none of these explanations is satisfactory. In my opinion a much better bet is the theory that the constancy scaling mechanism is triggered by these shapes, and that this is inappropriate because the pictures are flat. This has also been considered by a German worker named Tausch. I will now try to describe why these kinds of shapes should trigger the constancy mechanism inappropriately.

I think you will agree that the first figure I described is like railway lines running to the horizon. Now consider the second figure. Look at the corner of your room, and note the line the

walls make with the ceiling, and also the line the walls make with the floor. You will see that these lines make the same figure as the arrow with the outgoing fins. Now look at the edge of a box—the line of the top and bottom will form a second arrow shape; but this time they are ingoing fins. In other words, the two figures drawn on paper are the same as the flat retinal images in your eyes corresponding to corners lying in three-dimensional space.

All the traditional illusion figures represent on a flat plane the retinal images produced by perspective of corners or lines going to vanishing points. Although this has been noticed by several workers studying visual perception, so far no serious attempt has been made to see whether the illusions can be explained by this common feature.

We are carrying out experiments to try to establish whether the illusions are caused by the constancy scaling mechanism being wrongly triggered by certain shapes, and so producing distortion of perceived space. The search for appropriate experiments has proved unusually interesting. I cannot describe them in detail now, or mention them all, but I will try to give an idea of some of them.

First, let us ask whether the distortions go the right way. In the first illusion—the railway line figure—the top horizontal line would be the farther away if it were lying in three dimensions, the non-parallel lines being perspective lines. Now the retinal image of a further object will be smaller than the image of a nearer object of the same size, but the constancy mechanism normally makes them appear very nearly the same size. To do this the image of the farther object must be effectively expanded. This is evidently what happens in the railway line illusion: the line which would be further if it were lying in three dimensions is expanded, by the constancy mechanism in the brain, to look the same size; but since in the drawing the images are actually the same size, it looks larger.

The case of the arrow figure is similar. The outgoing arrows would generally correspond with the corner of a room. The vertical shaft of the arrow would be farther away than the ends of the fins if it was a corner in three dimensions. The arrow figure with

the outgoing fins has been elongated with the illusion, and this is the right way round for the theory. Similarly, in all the various illusions, the distortion does go the right way round.

If the illusions are indeed due to constancy scaling being misplaced because the display is flat, then we should expect three-dimensional models of the figures to show less illusion. This we have done for the arrow illusion. Miss C. D. Shopland used a pair of three-dimensional arrows, one of which could be adjusted in length with an electric motor controlled by either subject or experimenter. The display was arranged to glow in the dark. She found that the illusion is greater for the three-dimensional display when viewed with one eye, and thus seen as flat, than when seen as a three-dimensional figure using both eyes. This we predicted from the theory.

If various illusions are combined in one display, it is found that they do not add arithmetically. Only a small increase to an illusion can be made by adding a second illusion. Now, we could try adding constancy to an illusion, and we should predict that the illusion will not be greatly increased if the same mechanism underlies both constancy and illusions. We have tried viewing the arrow illusion from an angle, so that the retinal image of the shaft is lengthened by constancy, and we find that once constancy has stretched the line the fins will not stretch it any more. This also we predicted from the theory. What now happens under conditions when constancy does not operate? It is well known that constancy ceases to work at great distances: do the illusions occur when the display is at a great distance? We are investigating this, but so far have no answer.

In the case of the drawings on paper the texture of the paper tells you that the figure is really flat—lying on the paper—while the perspective lines trigger off constancy appropriate to objects lying in depth.

If now we can remove all texture (by making figures from wire and coating them with luminous paint so that they glow in the dark) there should be nothing to tell the visual system that the figures are really flat. If we have arrows with very acute angles, then the illusion still occurs and the figure is seen as more or less

flat. (I should say here that these figures are viewed with one eye so that there is no other information to tell the visual system that they are really flat.) Now if we make our wire models of the arrows with much larger angles—almost like capital I's—then an interesting thing happens. The figures are seen as though they lie in depth—like corners—and the illusion disappears. Using these glowing figures, which have no background, there is nothing to indicate that they are really flat and so their perspective makes them appear truly three-dimensional, and there is now no illusion provided the vertical lines of the arrows seem to be at the same distance from the observer.

If we make a wire model of two overlapping squares, one square will seem to rise above the other in a quite odd way, and it will look like a hollow cube. Either square may appear in front of the other, but what is important is that whichever square is apparently in front looks smaller than the square apparently at the back, though in fact they are the same size. This shows that the constancy mechanism can operate simply from apparent distance in the absence of any depth information.

In the case of illusion figures drawn on paper with texture telling the visual system that the figure is really flat, angles normally indicating perspective can serve to trigger the constancy system inappropriately. This should give an illusion. But if there is no texture fixing the figure in a flat plane, then perspective lines will make the flat figure lie apparently in depth. When it is seen in depth distortions occur. Whenever the constancy is inappropriate to the distance we have an illusion.

This explains something you have probably seen, that the moon looks much larger on the horizon than when it is high in the sky. Here the constancy mechanism in the brain enlarges it because it looks farther away when there are objects lying in front of it, which only occurs when it is low down on the horizon.

Illusions can be party games; they can produce disasters in driving or flying, and they can provide clues to understanding how the perceptual system works. They are amusing, dangerous and interesting—what more can one ask of anything in life?

What Gives the Salt its Savour?

BY PROFESSOR G. M. WYBURN

Taste and smell are our chemical analysers, providing us with a service which no chemical laboratory can hope to rival. The results are produced in a fraction of a second compared to hours or even days required for laboratory tests, and can be given with samples many hundred times smaller than the chemist needs.

Asked how many kinds of taste there are, most people would answer hundreds or even thousands. In fact, there are four basic tastes—acid or sour, salty, bitter, and sweet. Blended in various combinations these four tastes are responsible for the many flavours of the food we eat, just as the colours we see in the rainbow are mixtures of three primary colours. Most flavours, however, owe something to the sense of smell, and, for example, when we have a cold in the head our food loses much of its savour.

Put your tongue out, and far back on its upper surface you can see a V-shaped row of raised plaques or papillae about a millemetre in diameter, each encircled by a shallow trench. In the walls of this trench, but too small to be seen with the naked eye, there are taste organs or receptors known as taste buds. Taste buds are also found related to papillae at the tip and at the sides of the tongue, and altogether the human tongue has from 9,000 to 10,000 taste buds. The number, however, tends to decrease in later years, hence the jaded palate of the elderly epicure seeking new and exotic dishes to stimulate his dwindling taste perception.

Seen with the microscope each taste bud consists of a cluster of thin leaf-like cells cemented together at the apex which lies below the surface in the taste pit. A slender process of material secreted by these cells often projects from the taste pit. Fine nerve twigs terminate in expansions on the surface of the cells of the taste bud.

Although the taste buds all look alike, even when studied with the electron microscope at a magnification of 50,000 or more,

different parts of the tongue are specially sensitive to particular kinds of taste—sweet tastes at the tip, acid tastes at the sides, and bitter tastes at the back. (The small flake of tobacco escaped from the cigarette is only recognised when its bitter taste is recorded at the back of the tongue.)

Our senses have three parts: first, the sense organ or receptor at the input end gathering information; second, the nerves or conducting elements conveying this information to the brain; and third, the receiving centres in the brain responsible for the output in terms of perception: that is, what we taste, what we see or what we hear.

The receptor apparatus carries out two separate tasks. First, they are constructed so that normally they record only one kind of stimulus. For example, the taste buds deal with chemical stimulation—they are chemoreceptors—the photoreceptors of the eye react to light, and in the skin and elsewhere mechanoreceptors register touch or pressure. Secondly, receptors are biological transducers in that they transform one kind of energy—the energy of the stimulus—into another kind of energy—electrical energy—which is used to send coded messages along the nerves and up to the brain. (An example of a modern man-made transducer is the microphone.)

The development of the necessary delicate tools, microelectrodes fine enough to be inserted into cells a few thousandths of a centimetre in size, and instruments capable of measuring electric currents in millivolts, that is, a thousandth part of a volt, have made it possible to find out what happens inside a receptor when it is stimulated. We now know that within a thousandth of a second from the time of stimulation a taste bud generates a positive electrical charge known as the receptor potential, which is of the order of millivolts, the strength depending on the intensity of the stimulation. This is brought about by a change in the outside covering or cell membrane of the receptor whereby particles with a positive electrical charge—cations such as sodium, for instance—pass into the receptor.

The receptor potential, like a miniature electric battery, is used to trigger off volleys of electrical impulses which are sent along

the nerves, and the information about the stimulation is received by the brain in the form of these nerve impulses, which can be regarded as a biological morse code with dashes but no dots. The stronger the stimulation the larger is the receptor potential, and the greater the number of nerve impulses sent off. It is important to realise that the only kind of message received by the brain, whether it is from the eye, ear, or the taste buds, is in the form of nerve impulses.

As there are four basic tastes it would be logical to expect that each taste would stimulate its own group of taste buds. The position, however, is much more complicated. It is experimentally possible to record the discharge of nerve impulses in the nerve of a single taste bud stimulated with substances of different tastes, and in this way it has been shown that most taste buds respond to more than one kind of basic taste although they may be more sensitive to a particular taste as indicated by the discharge of a greater number of impulses. To put it another way, each of the four basic tastes might stimulate taste buds which also respond to one or more of the other three tastes, but the frequency ratio of the group discharge would be different for each taste.

I have already said that each taste bud consists of a cluster of cells. It is possible to insert a micropipette into the separate cells of a taste bud and to demonstrate that each cell behaves as the whole taste bud and responds to more than one basic taste.

The stimulus energy for the photoreceptors of the eye is, we know, provided by a range of electro-magnetic radiation and, for the mechanoreceptors of the ear, by the pressure of sound waves, but our knowledge of the nature of the taste stimulus is much less precise; nor can we relate the energy of the stimulation to the quality of the perception as we can, for example, colour to the length of the light waves, or pitch to the frequency of the sound waves.

We all know what kind of substances have an acid taste, a salty taste, a bitter or a sweet taste, and we also know a great deal about the physical and chemical properties of such substances in solution, any one of which could be the source of the stimulus energy to generate the transducer action of the taste receptors. Sapid

substances, that is, substances with a taste, are either in solution or dissolve in saliva.

Substances which when in solution can conduct electricity are called electrolytes, and electrolytes contain ions or dissociated particles with an electric charge. Ions with a positive charge are cations, those with a negative one are anions, and we have found that such ions are concerned with at least two of the basic tastes —acid and salty. Professor Pfaffman of the U.S.A. suggests that ions, with their positive or negative electric charge, become loosely attached to special molecules on the receptor surface of the cells of the taste buds, and there initiate the change responsible for the development of the receptor potential.

The chemical characteristics of an acid are based on its content of free particles of hydrogen which are cations (that is ions with a positive charge). This is expressed as the hydrogen ion concentration and is indicated by the symbol pH, and the greater the number of free hydrogen ions the stronger is the acid. A normal solution of hydrochloric acid, for instance, contains 186 times more hydrogen ions than a normal solution of acetic acid. The sour or acid taste is linked to the hydrogen ions. The relationship is not, however, direct; although acids all taste sour, weak acids such as acetic with their lower concentration of hydrogen ions can taste just as sour as a solution of inorganic acids with higher concentrations of hydrogen ions; and, moreover, solutions of the inorganic acids with equal pH's do not necessarily taste equally sour. The electric conductivity of an acid solution is mathematically related to its pH and also appears to be concerned in the taste stimulus. There are probably other factors which affect the speed with which the hydrogen ions can reach the effective receptor zone of the cells of the taste buds.

Now what about the salty tastes? All substances with a salty taste are soluble salts with cations and anions, both of which contribute to the taste stimulus. Common salt, where sodium is the cation and chloride the anion, is the only pure salty taste. In other salts the quality of the taste varies with the anion. Salts of heavy metals such as mercury, with a high molecular weight, have a metallic rather than a salty taste. Professor Nivol of Glasgow has

shown that the significant physicochemical properties of a salt taste are, first, the effective molecular weight, that is the molecular weight of the salt divided by the number of ions per molecule. With common salt the molecular weight is 58; there are two ions—sodium and chloride—to give an effective molecular weight of 29.

The second factor is the ratio of the weight of negatively charged anions to positively charged cations; we refer to this ratio as 'G'. For common salt G has a value of 1·45. Where the value of G is as high as 2·5 the salt taste tends to change to bitter. Professor Pfaffman has pointed out that for each species of animal there is a different graded series of anions and cations for degrees of saltiness, and this series in some ways may be related to differences in the ion composition of the body fluids in the different species.

Although the precise details are lacking, it can be safely stated that salty, like acid, taste is the way in which we all, without any knowledge of chemistry, recognise the ion population and ratio of distribution within a solution.

Up to the present we have not been able to link the sweet or bitter taste with any particular physical or chemical property. Because it is an obvious property of sugar solutions, osmotic pressure is suggested as the stimulus energy for the sweet taste. Certainly, if you dilute salt solutions until they lose their salt taste, but still possess osmotic pressure, they taste sweet. There is, however, little chemical connection between the sugars and the synthetic sweeteners like saccharine, where osmosis does not apply.

The bitter taste is even more puzzling, with a range of such chemically different substances as quinine, nicotine and epsom salts. Some substances, moreover, can taste both sweet and bitter.

The primary purpose of taste is the rejection or acceptance of food by the organism, and a conscious sensation of taste is probably limited to those animals with well-developed brains. It should be remembered that our sensory mechanisms are not windows looking out on the external world, but create the biological symbols which are the basis of our perceptions. For

example, certain pressure waves we interpret as sound, others we feel as vibration. Taste, therefore, like the colour of the sunset or the music of a symphony, exists only within the brain and the saying that what is one man's meat is another man's poison is merely a way of stating that no two brains are exactly alike in the details of their structure or the more subtle aspects of their function.

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